TURBOMACHINERY COURSE

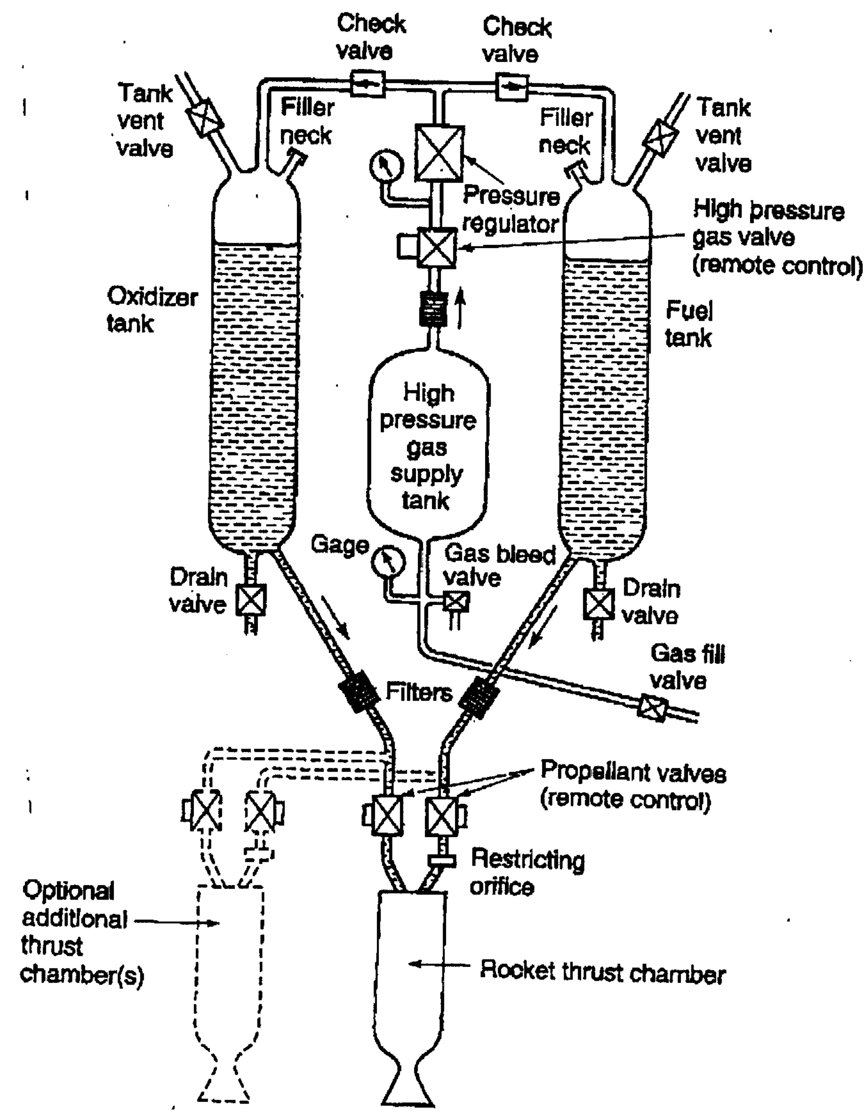
- What is a turbomachine?
  - A piece of machinery driven by a turbine.
- What is a liquid rocket engine turbopump?
  - Assembly of a turbine with one or more pumps

    (Sutton, page 362)

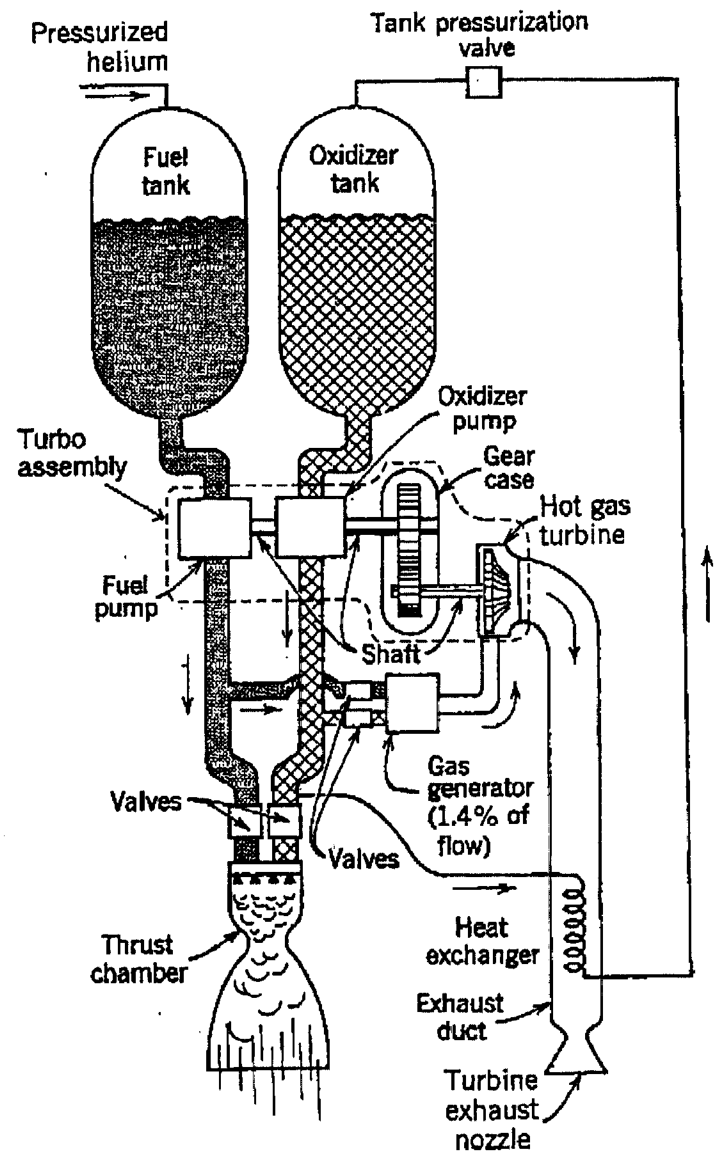
TURBOMACHINERY COURSE

- Why use a turbopump?
  - Liquid rocket engines can be pump–fed or pressure–fed.

TYPICAL PRESSURE–FED SYSTEM



TYPICAL PUMP–FED SYSTEM



PRESSURE–FED SYSTEMS

- Advantages
  - Less complex
  - Less development required
- Best suited for low thrust application
  - Reaction control system
  - Orbital maneuver systems
  - Historically less than 6000 lbf thrust

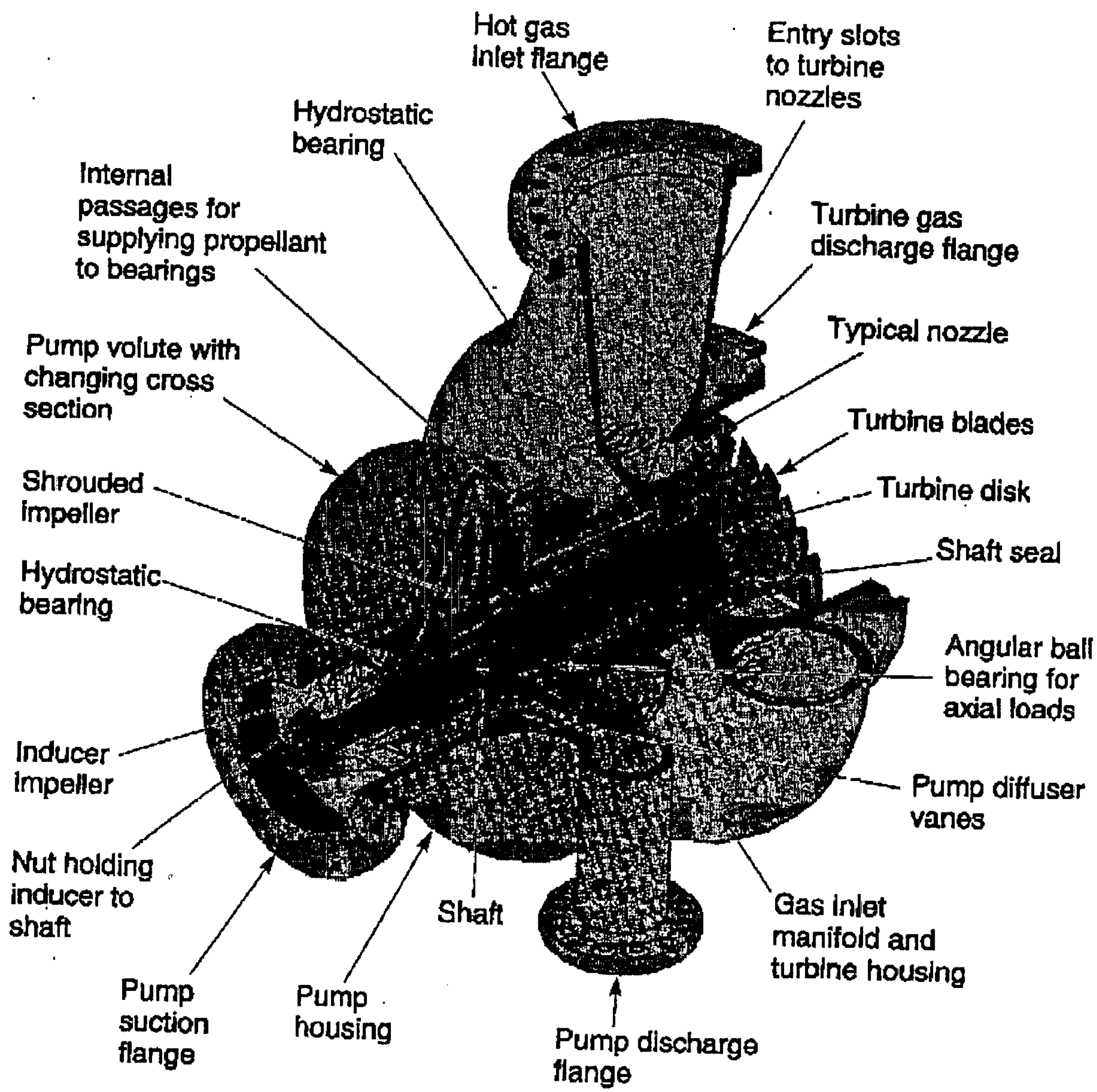
PUMP–FED SYSTEMS

- Advantages
  - Reduced system weight
  - High performance
- Best suited for high thrust and system requiring high velocities.
  - Boosters
  - High performance upper stages

BASIC ELEMENTS OF A TURBOPUMP

Element	Function
• Pump	Add energy to propellants via rotation
• Turbine	Derive energy from fluid to power the pump
• Bearings	Transmit loads from rotor assembly to stationary housings
• Seals	Prevent or minimize leakage, internal and external
• Couplings	Transmit torque between rotating elements
• Casings	Contain all elements and fluids

ROCKET ENGINE TURBOPUMP



PRINCIPLE OF TURBOMACHIERY OPERATION

- Energy added or removed from a fluid by a transfer of angular momentum between the fluid and a rotating element.
- Changes in angular momentum require changes in tangential velocity
- Pump
  - Rotating blades increase tangential velocity
  - Stationary blades decrease tangential velocity

PRINCIPLE OF TURBOMACHIERY OPERATION

- Turbine
  - Rotating blades decrease velocity
  - Stationary blades increase velocity
- Pump flow process
  - Diffusion process where kinetic energy is converted to pressure
  - Shaft power produces kinetic energy and potential energy.

PRINCIPLE OF TURBOMACHIERY OPERATION

- Turbine flow process
  - Expansion process where pressure is converted to velocity
  - Potential energy is converted kinetic energy and shaft power

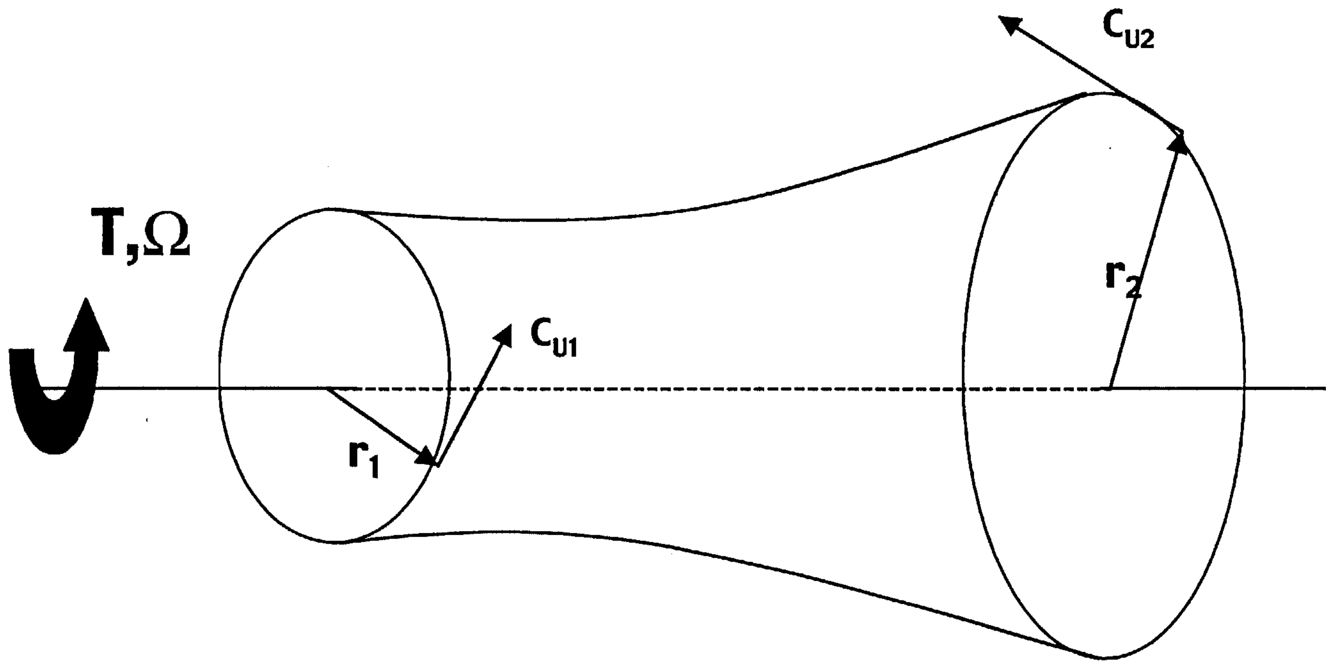
EULER PUMP EQUATION

- Pump
  - Pump head rise is pressure increase expressed in feet of liquid pumped
  - $\Delta H = (P_d - Pi)/\rho$
- Euler equation relates head to changes in velocities
  - Conservation of angular momentum relates shaft torque to fluid velocities

EULER PUMP EQUATION

- Power can be related to torque and head which gives head in terms of fluid velocities and efficiency.
  - Let T = Torque
    M = Mass Flow
    Ω = Rotational Speed
    Cu = Tangential Velocity
    ΔH = Head
    η = Efficiency

EULER PUMP EQUATION



Angular Momentum: $T = M\{r_2C_{u2} - r_1C_{u1}\}$

$T\Omega = M\Omega\,\{r_2C_{u2} - r_1C_{u1}\}$

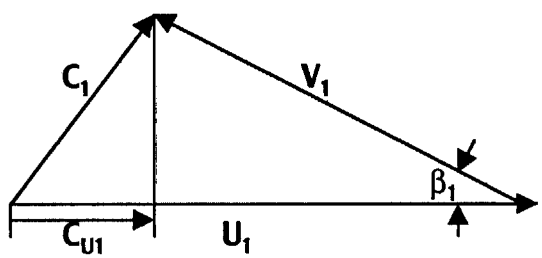
Shaft Power $T\Omega = Mg\Delta H/\eta$

Thus $\Delta H = \eta\Delta(UCu)/g$

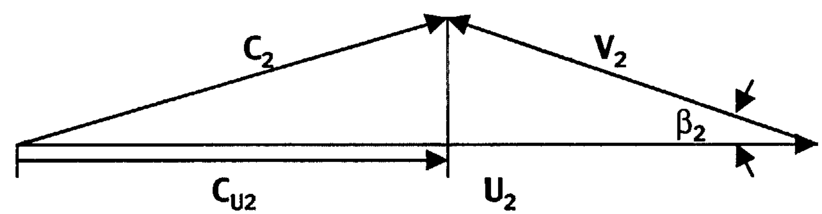
Euler Head $\Delta H_E = \Delta(UCu)/g$ = Ideal Head

IMPELLER VELOCITY DIAGRAMS

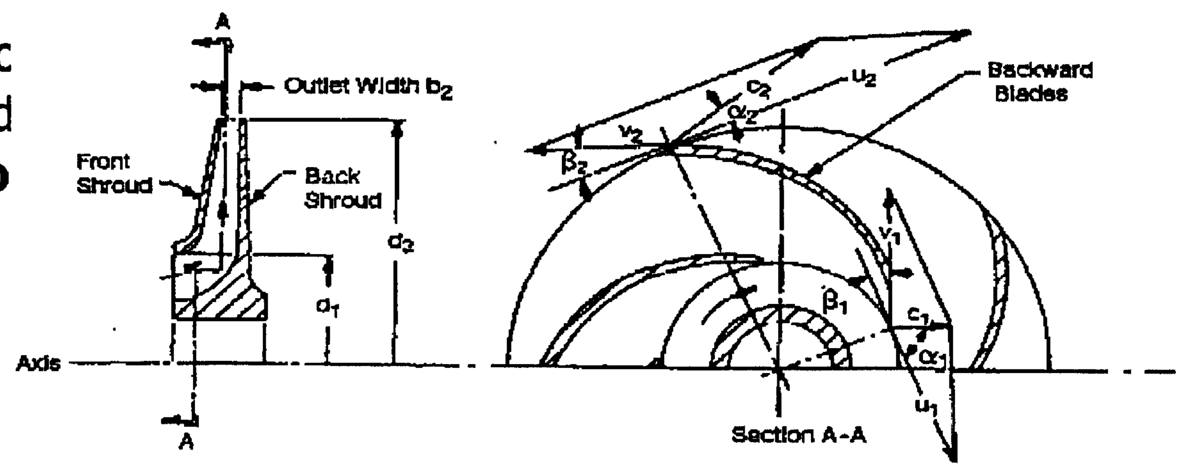
Inlet Velocity Diagram



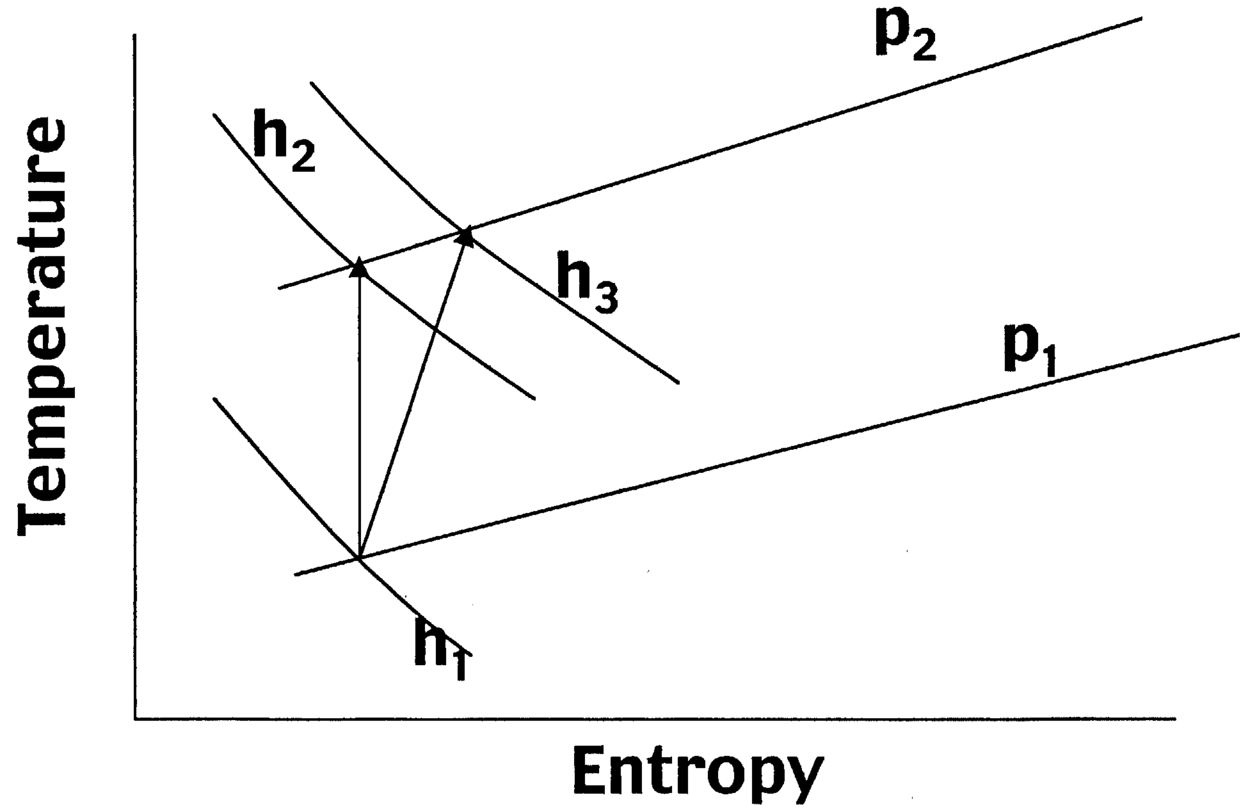
Outlet Velocity Diagram



U = Impeller peripheral velc
C = Absolute velocity of fluid
V = Flow velocity relative to
impeller
1 = Impeller inlet
2 = Impeller discharge



THERMODYNAMIC PROCESS



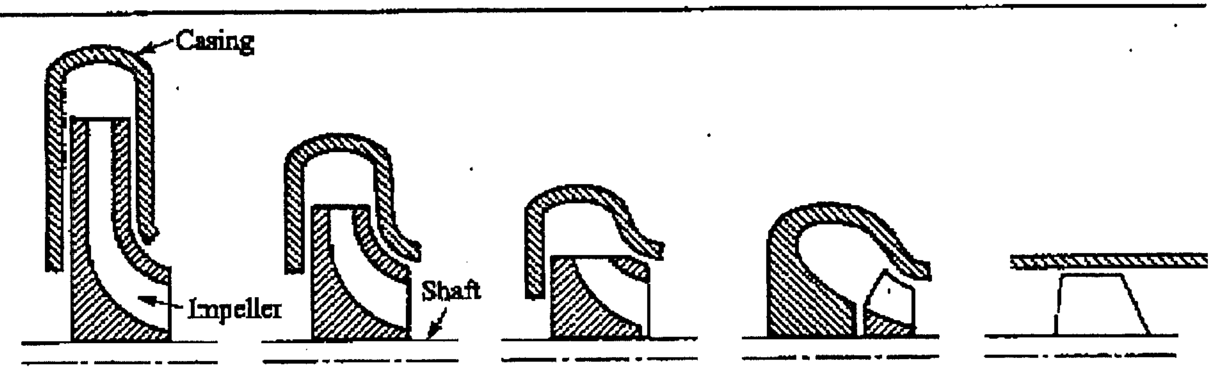
PUMP PARAMETERS

$\Delta H = h_2 - h_1$	head rise across pump, ($ft-lb_f/lb_m$)
$\Delta H = (p_2 - p_1)/\rho$	for incompressible fluids
$\eta = (h_2 - h_1)/(h_3 - h_1)$	pump efficiency
$m =$	mass flow, (lb_m/sec.)
$P = m\,\Delta H/\eta$	Shaft power required, (HP)
$\Psi = \Delta H/(U^2/g)$	Head Coefficient, dimensionless
$Q =$	Volumetric flow, (ft^3/sec)
$A =$	Flow area at impeller tip, (ft^3)
$\Phi = C_m/U$	Flow Coefficient, $C_m = Q/A$
$N =$	Shaft speed, (rpm)
$N_S = NQ^{1/2}/(\Delta H)^{3/4}$	Stage specific speed, (rpm,gpm,ft)

PUMP TYPES

- **Stage Specific Speed Defines Pump Type**

TABLE 10-2. Pump Types

	Impeller type				
	Radial	Francis	Mixed flow	Near axial	Axial
Basic shape (half section)					
Specific speed N_s					
U.S. nomenclature	500–1000	1000–2000	2000–3000	3000–6000	Above 8000
SI consistent units	0.2–0.3	0.4	0.6–0.8	1.0–2.0	Above 2.5
Efficiency %	50–80	60–90	70–92	76–88	75–82

PUMP EFFICIENCY

- **Efficiency Related to Stage Specific Speed**

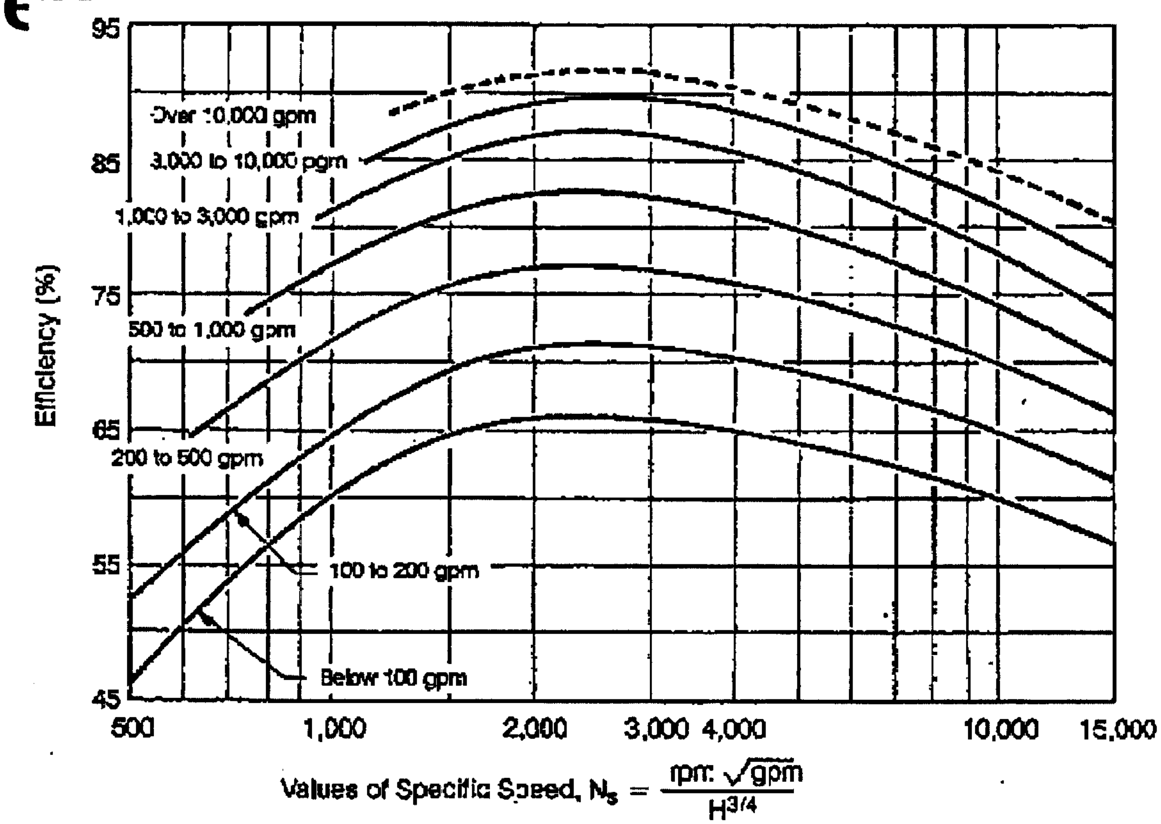


Fig. 6-23 Variation of pump efficiency with specific speed.

TYPICAL PUMP PERFORMANCE MAP

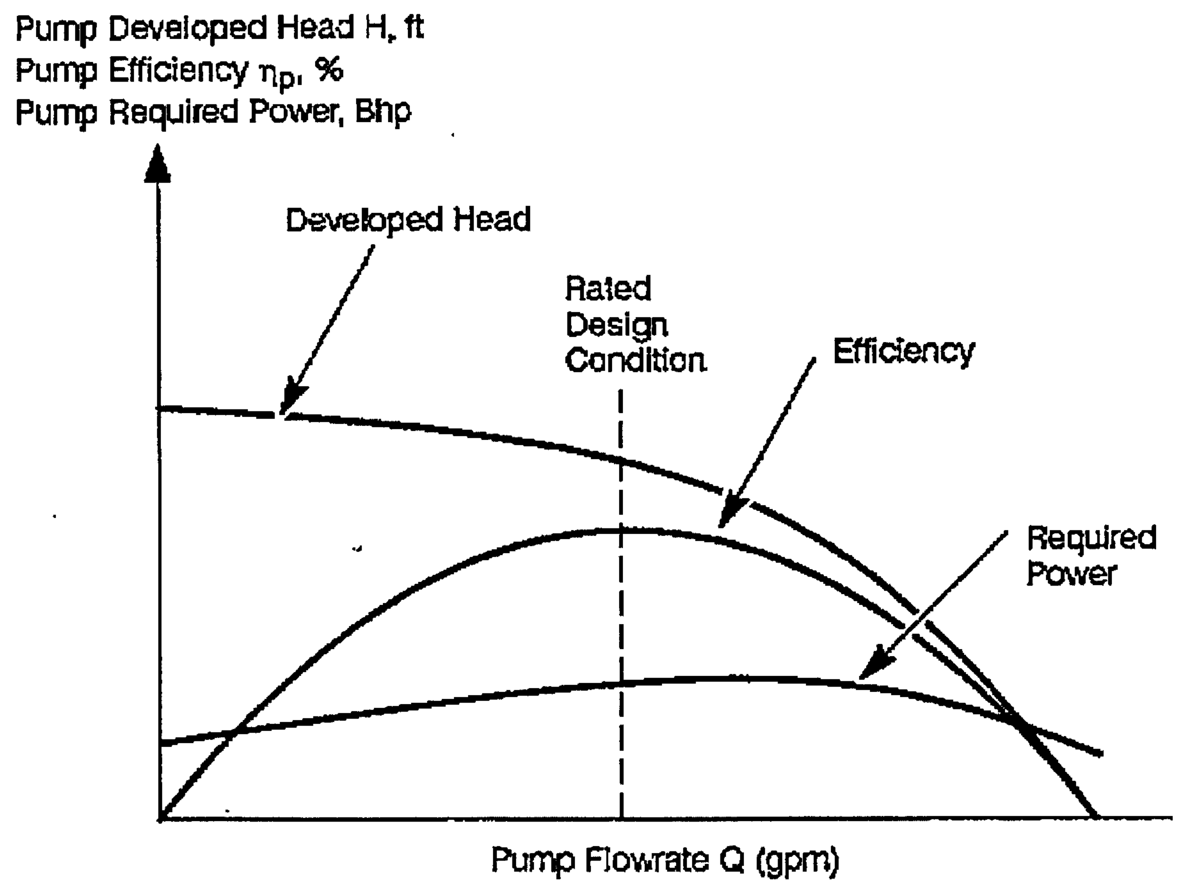


Fig. 6-24 H-Q, efficiency, and required power characteristic curves of a typical centrifugal pump.

PUMP SUCTION PERFORMANCE

- Pump performance dependent on pump inlet pressure
- Cavitation develops if static pressure drops below vapor pressure.
  - Net Positive Suction Head (ft.) defined as:
    - Total Head above Vapor Head, ft.
    - $NPSH = P_S/\rho + C^2/2g - P_V/\rho$
      - P_S = Local Static Pressure, psf
      - C = Local Velocity, fps
      - P_V = Vapor Pressure of Fluid, psf
      - ρ = Fluid Density, lb_m/ft^3

PUMP SUCTION PERFORMANCE

- Suction Specific Speed is Defined as
  - $N_{SS} = NQ^{1/2}/NPSH^{3/4}$
    - N = Shaft Speed, RPM
    - Q = Flow Rate, GPM
    - NPSH, Net Positive Suction Head, Ft.
- Available pump inlet pressure can significantly affect pump design
  - Operation at low inlet pressures required to reduce tank pressures and tank weight
  - Low inlet pressure operation (high Nss) often results in addition of an inducer, and/or a separate boost pump.

PUMP SUCTION PERFORMANCE

- Effects of cavitation
  - Performance
    - Head Loss
    - Efficiency Loss
  - Life
    - Can cause structural damage, pitting
    - High dynamic loads resulting in fatigue failures.

PUMP SUCTION PERFORMANCE

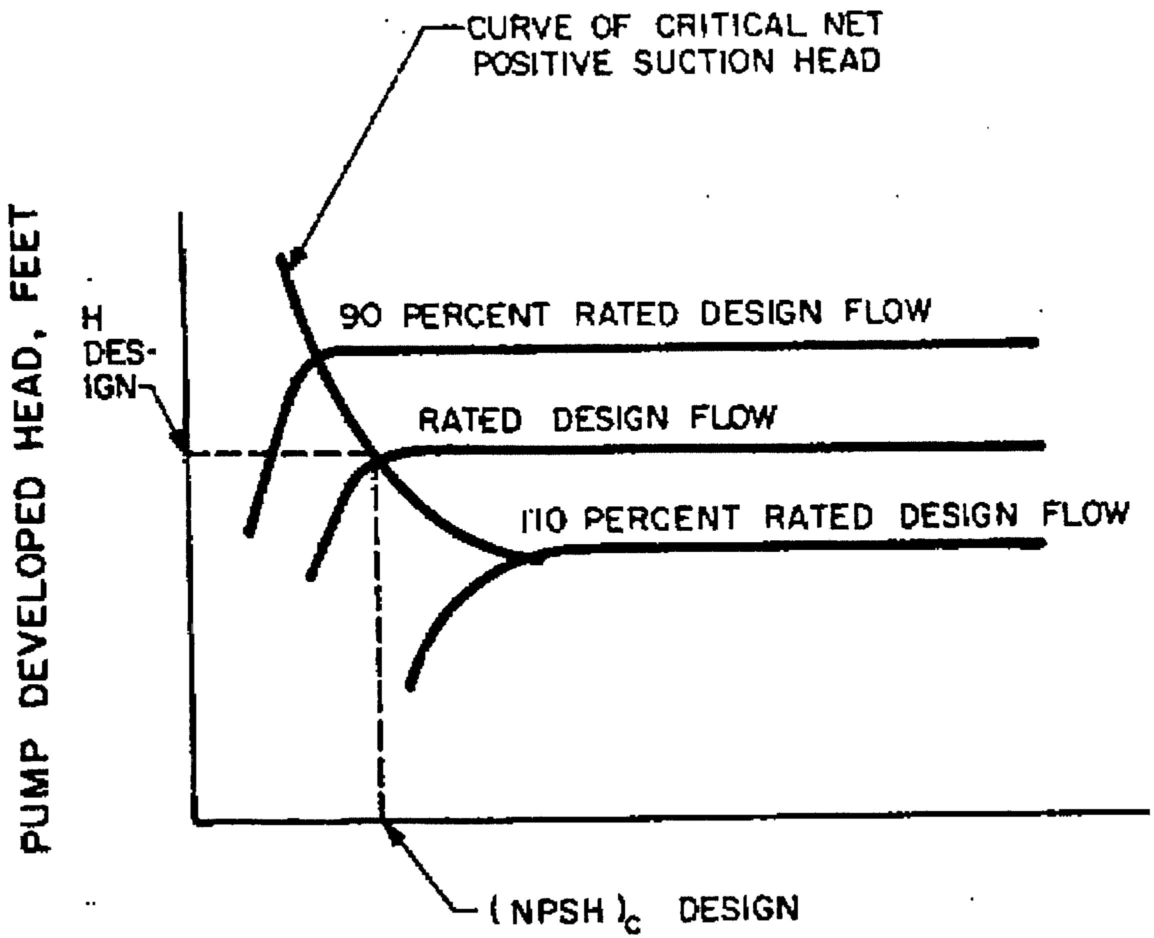


Fig. 6-21 Typical cavitation characteristics of a pump operated at rated design speed.

TURBINES

- Provide power to drive pumps
  - Energy derived from expansion of working fluid
    - High pressure, high temperature fluid at inlet
    - Low pressure, low temperature fluid at discharge
- Two primary turbine types
  - Impulse
  - Reaction
- Single and multiple stages
  - Single stage has one nozzle and rotor
  - Multi stage has multiple nozzles and rotors

TURBINES

- Impulse turbine
  - All expansion occurs in the nozzle
  - Rotor turns the flow , no fluid acceleration in rotor
- Reaction turbine
  - Fluid acceleration in both nozzle and rotor
- Impulse and reaction turbine can have multiple stages
  - Impulse
    - Velocity compounded
    - Pressure compounded

TURBINES

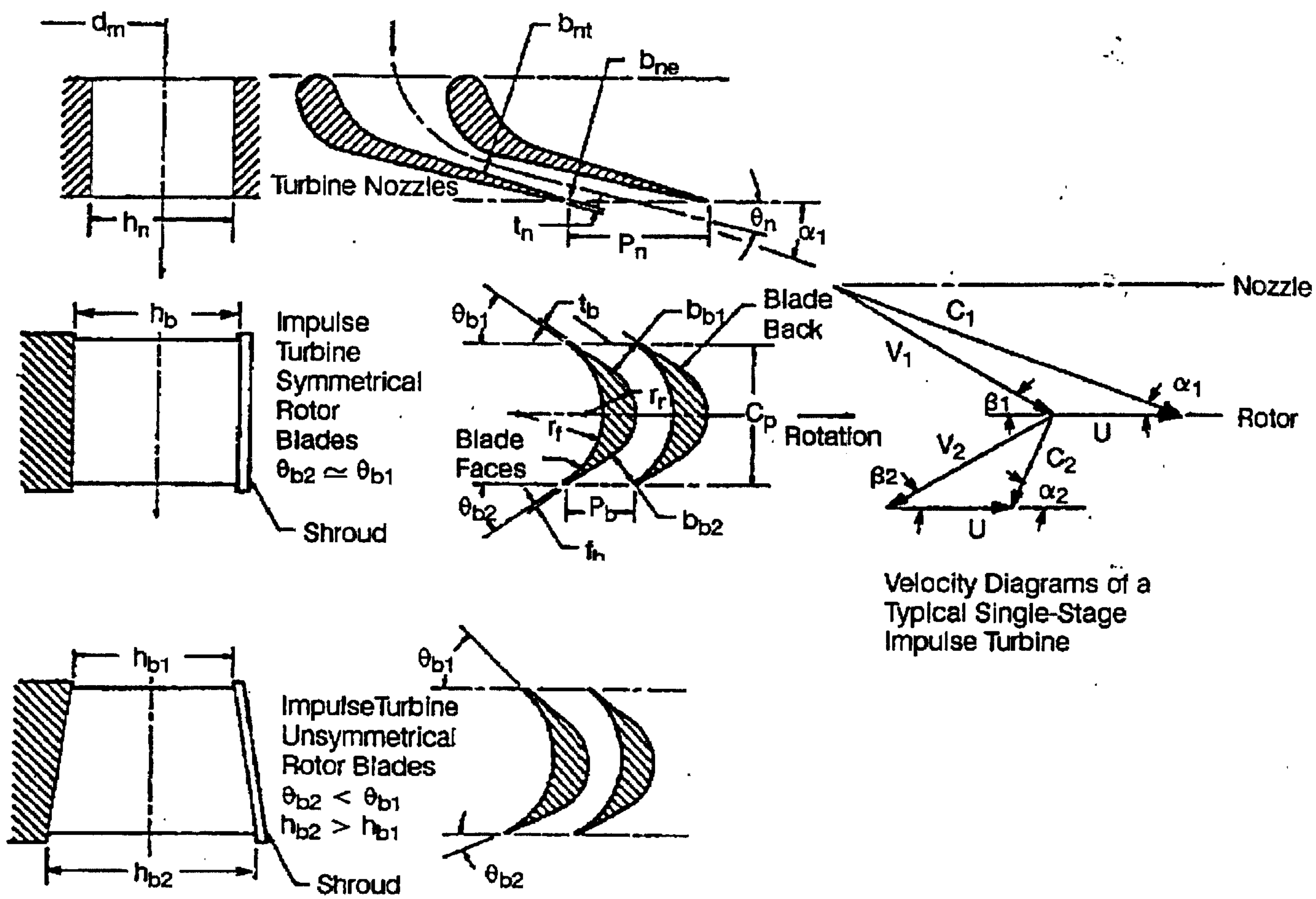
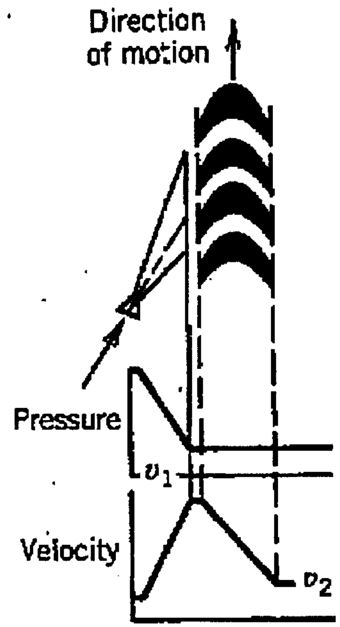
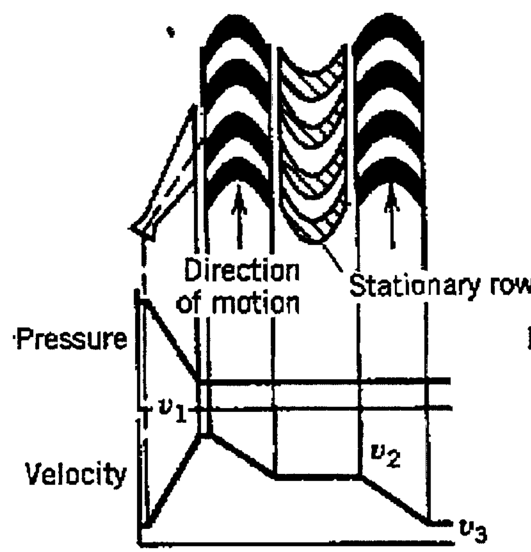


Fig. 6-55 Nozzles, rotor blades, and velocity diagrams of a typical single-stage impulse turbine.

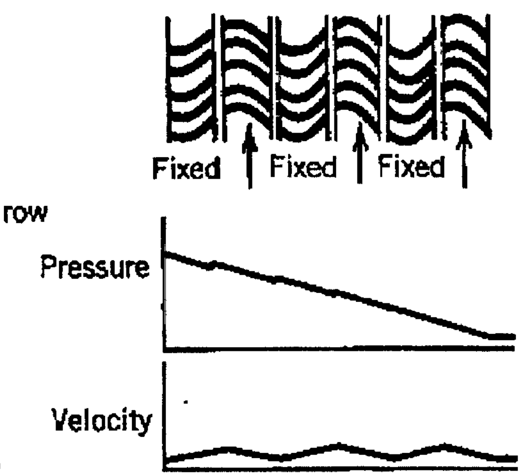
TURBINES



Single-stage, single-row impulse turbine



Single-stage, two-row velocity compounded impulse turbine



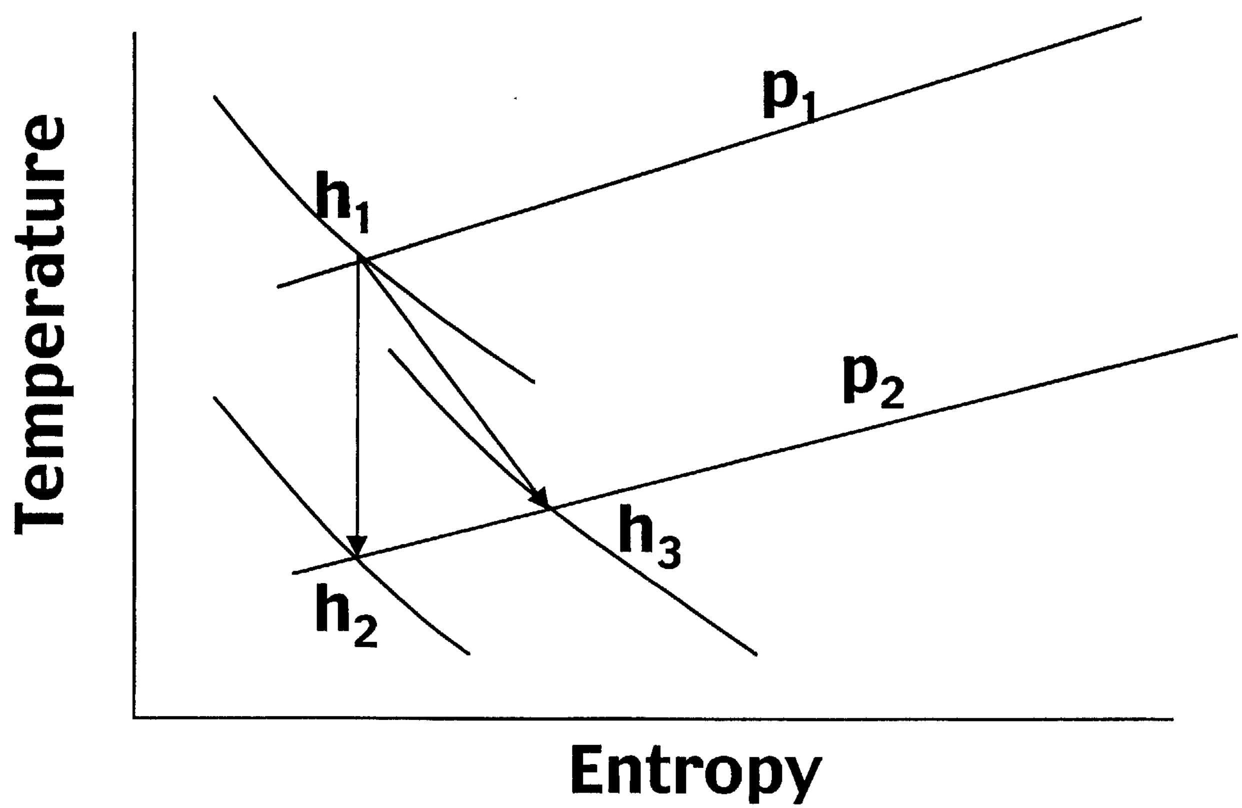
Three-stage reaction turbine, -50% reaction

TURBINE PARAMETERS

$\Delta H = C_P dt$	Turbine enthalpy drop
$h_2 - h_1 = C_P(T_2 - T_1)$	Assume compressible, Ideal gas
$\Delta H = h_2 - h_1$	
$\Delta H = T_1 C_P[1 - (1/P_R)^{(\gamma-1)/\gamma}]$	Available energy, Isentropic
$SHP = \dot{m}\Delta H\eta$	Shaft power, (HP)
$U = ND/229$	Pitchline Velocity, ft/sec
N	Shaft speed, rpm
D	Diameter, in
$C_0 = (2Jg\,\Delta H)^{1/2}$	Theoretical Spouting Velocity
$\eta = (h_3 - h_1)/(h_2 - h_1)$	Efficiency (isentropic)

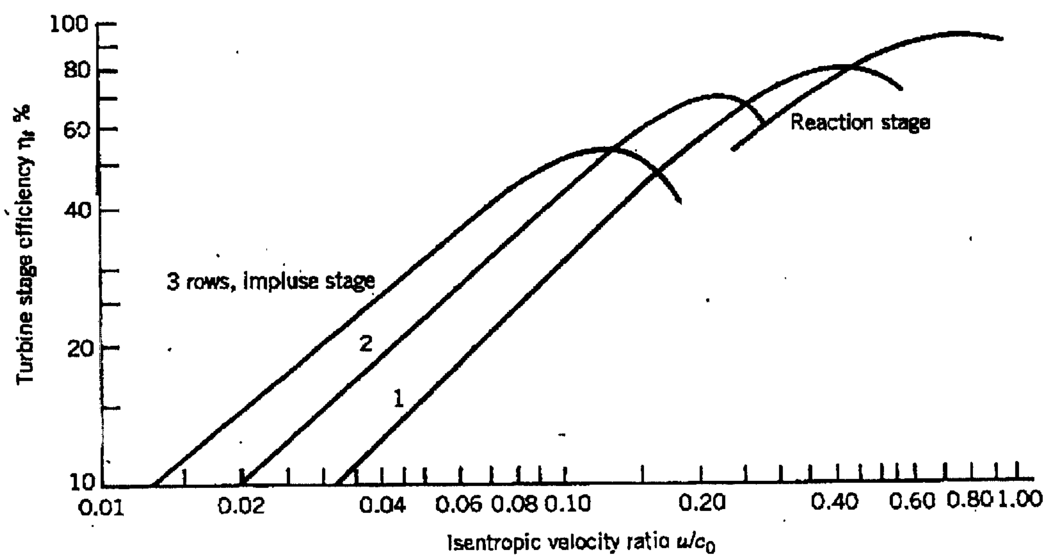
- η is a function of the number of stages and U/C_0

THERMODYNAMIC PROCESS



TURBINE EFFICIENCY

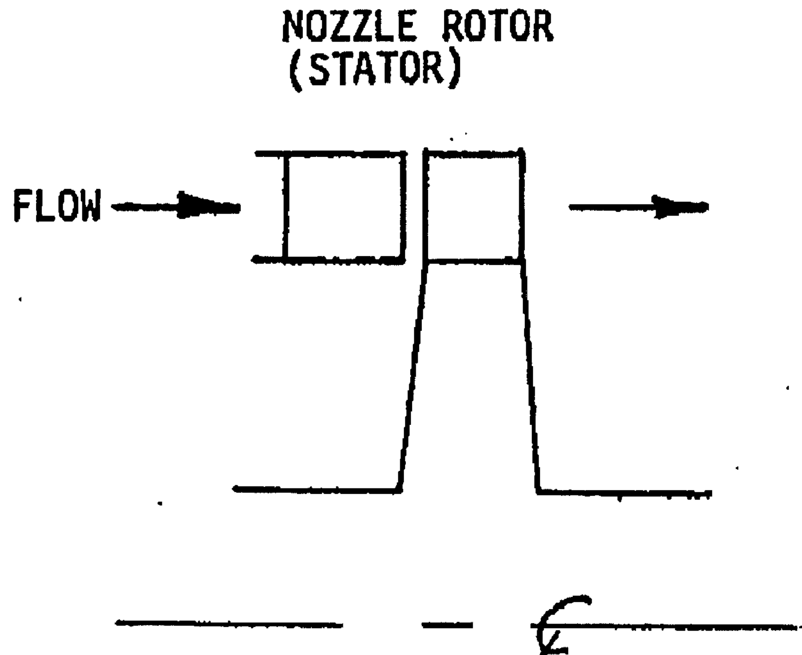
- Efficiency is a function of:
  - Type
  - Number of Stages
  - Velocity Ration U/C_0



TURBINES

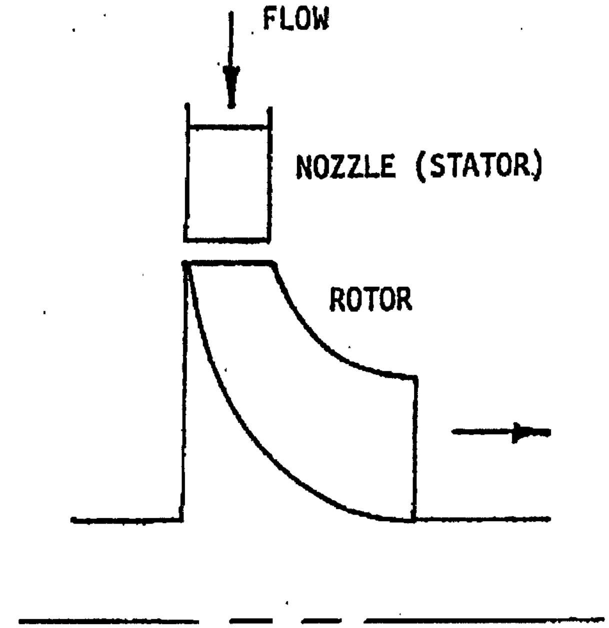
- In addition to types discussed thus far
  - Axial Flow Path
  - Radial Flow Path
- Axial Flow Path
  - Flow parallel to shaft centerline
  - Nozzle and rotor have same mean line
- Radial Flow Path
  - Flow enters perpendicular to shaft centerline
  - Flow exits parallel to shaft center line

TURBINES



AXIAL FLOW

- MOST ROCKET ENGINE TURBINES



RADIAL FLOW

- TURBOCHARGER TURBINES
- HYDROELECTRIC TURBINES

TURBINES

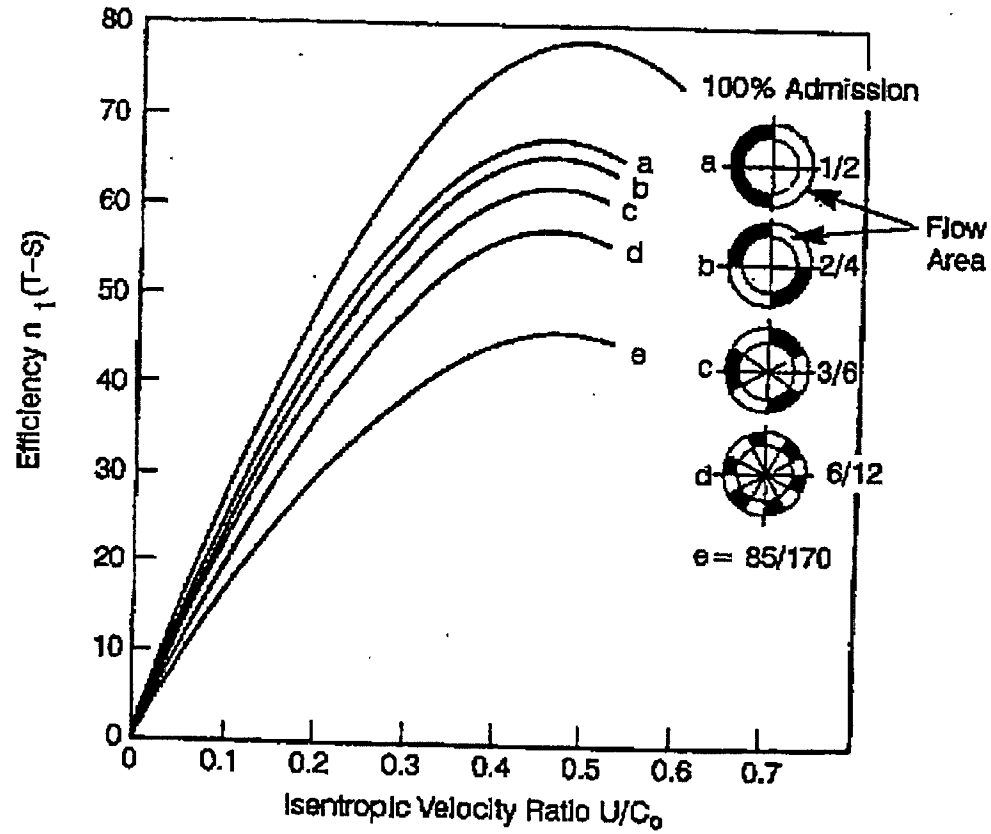


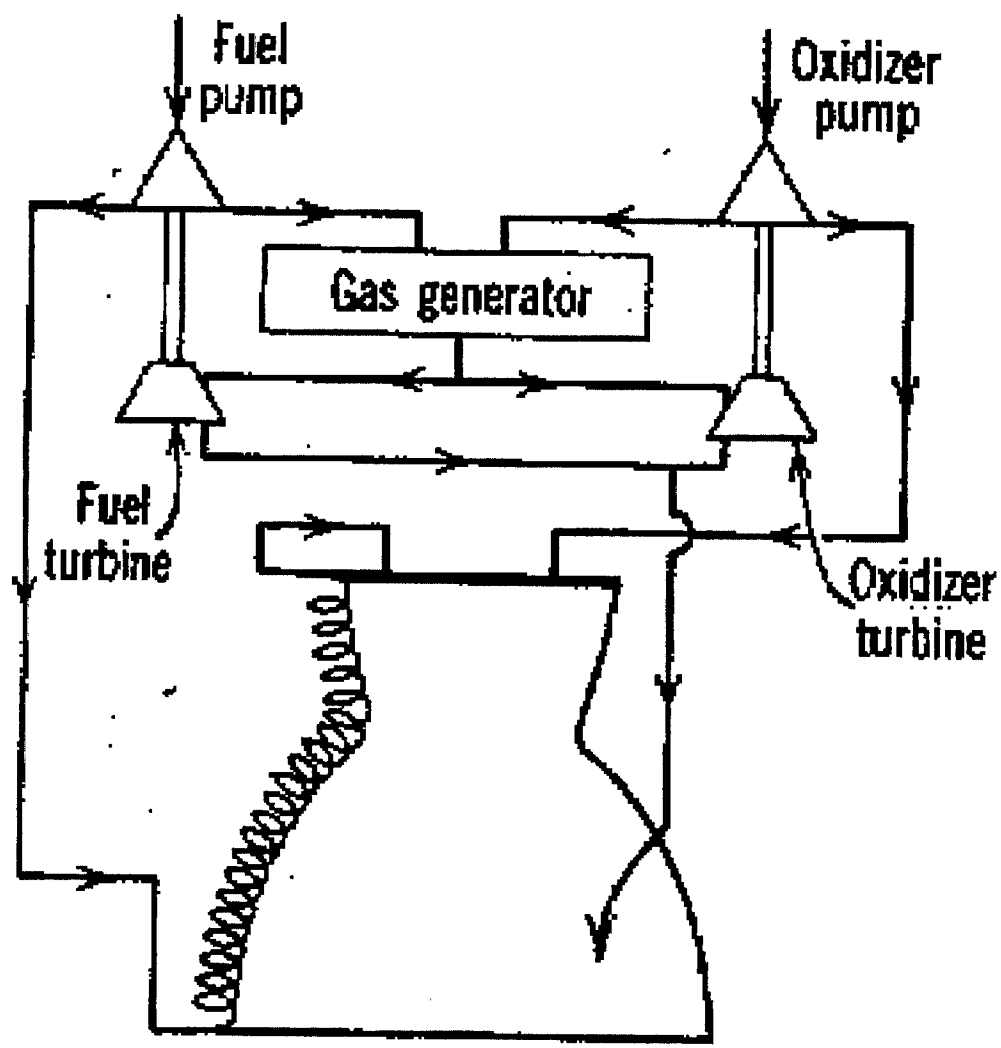
Fig. 6-56 Effect of number of active arcs on partial-admission turbine efficiency.

- Can be required for low flowrate turbine

ROCKET ENGINE CYCLES

- Engine cycle defines turbomachinery requirements
- Three basic engine cycles
  - Gas Generator
  - Staged Combustion
  - Expander
- Cycle name relates to the turbine drive source

ROCKET ENGNE CYCLES

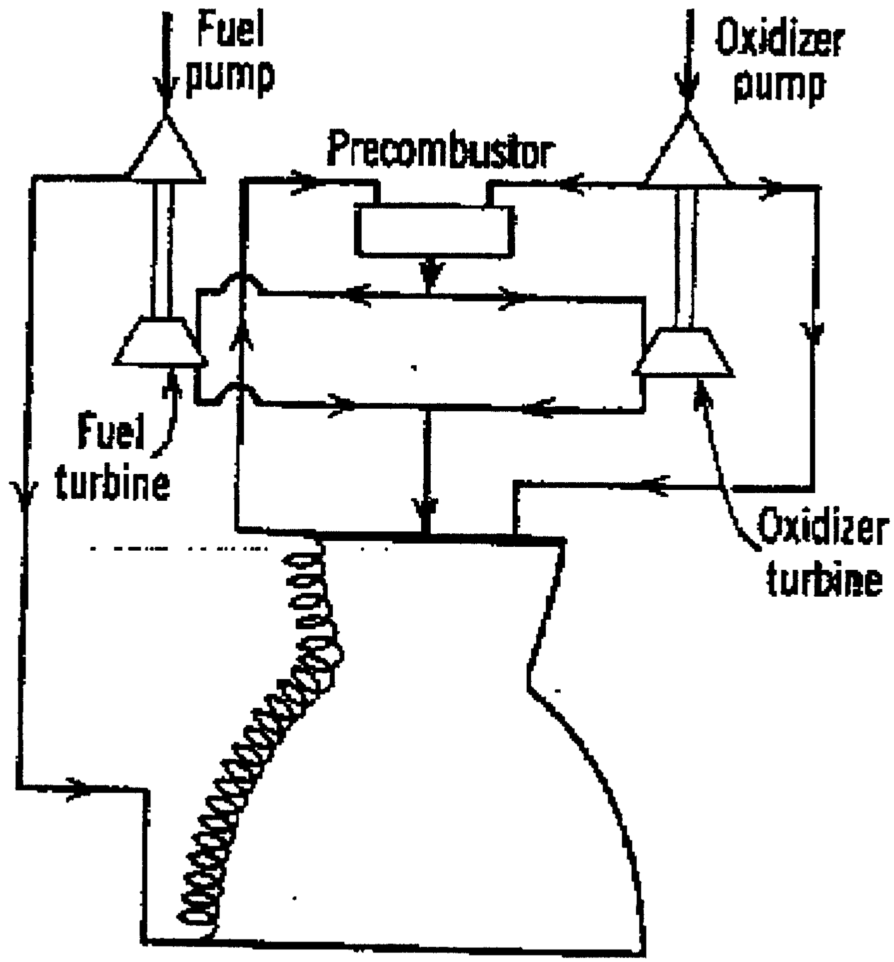


GAS GENERATOR CYCLE

ROCKET ENGINE CYCLES

- Gas Generator Cycle
  - Turbine is in parallel with the combustion Chamber
  - Pump discharge pressure set by thrust chamber pressure and thrust chamber injector delta pressure
  - Available turbine pressure high
  - Turbine flow reduces engine specific impulse
  - Turbine inlet temperature maximized to reduce turbine flow

ROCKET ENGINE CYCLES

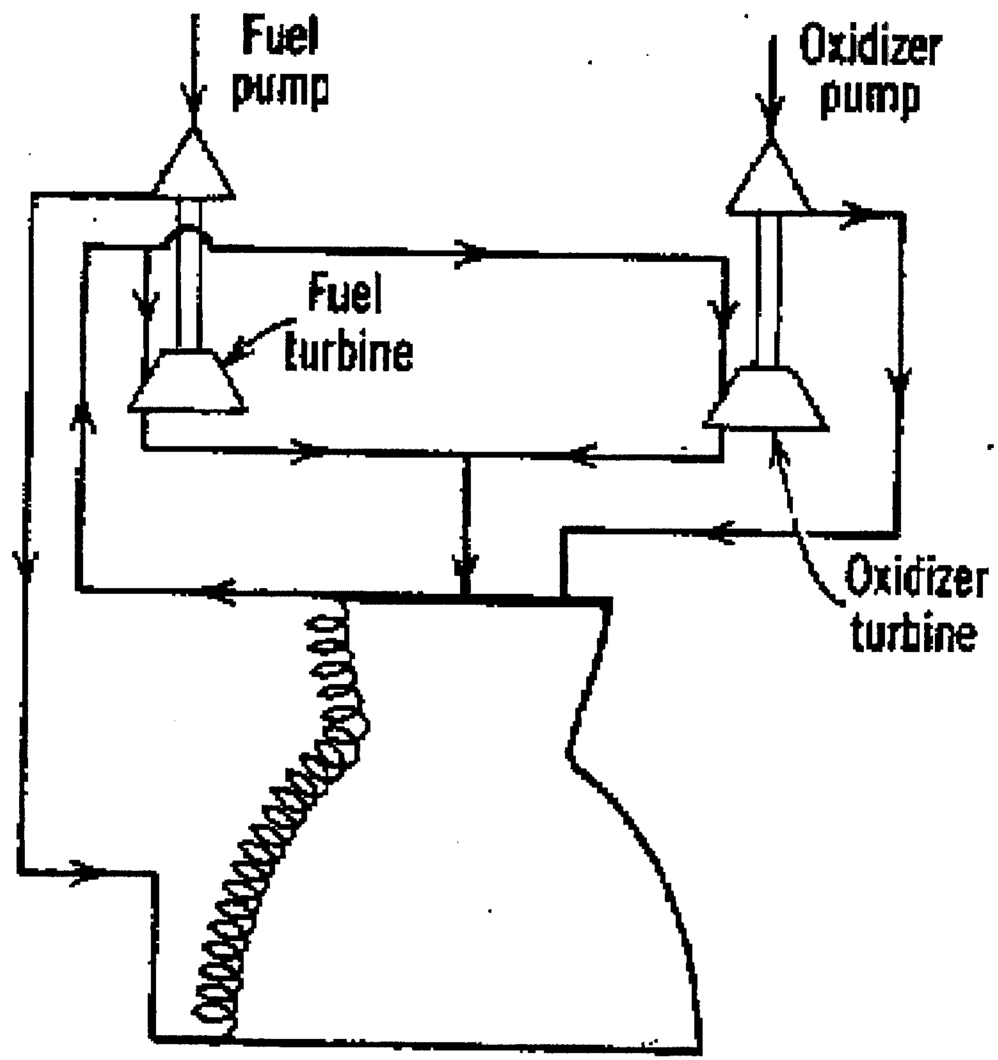


STAGED-COMBUSTION CYCLE

ROCKET ENGINE CYCLES

- Staged Combustion Cycle
  - Turbine and combustion chamber in series
  - Pump discharge pressure set by thrust chamber pressure, thrust chamber injector delta pressure, and turbine pressure ratio
  - Most of cycle fuel flow and small portion of oxidizer combusted in preburner
    - Fuel rich turbine drive
  - Increasing turbine inlet temperature decreases pump discharge pressure
  - Turbine flow does not affect engine specific impulse

ROCKET ENGINE CYCLES

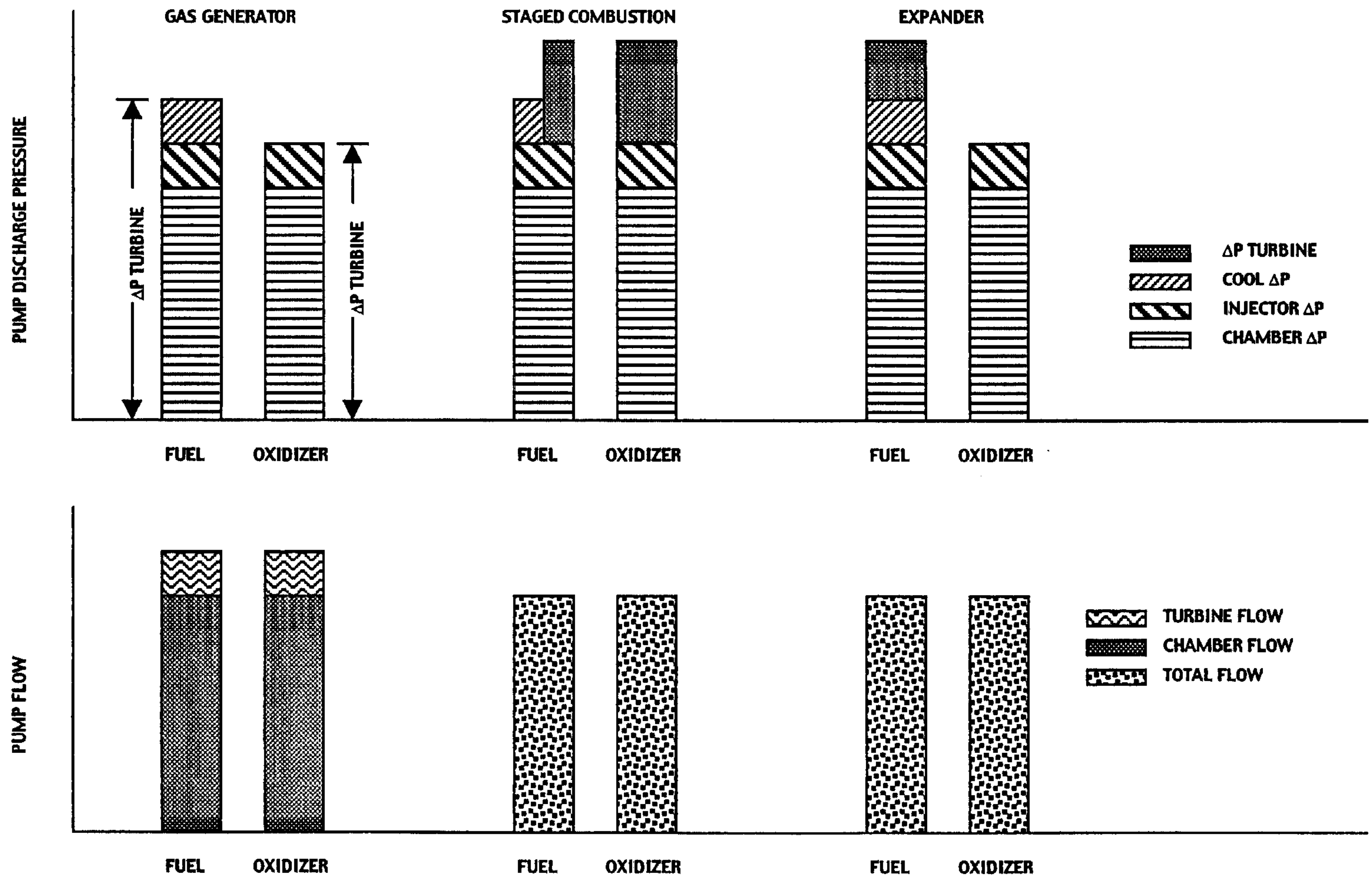


EXPANDER CYCLE

ROCKET ENGINE CYCLES

- **Expander Cycle**
  - Turbine and combustion chamber in series
  - Fuel pump discharge pressure set by thrust chamber pressure, thrust chamber injector delta pressure, and turbine pressure ratio
  - Oxidizer pump discharge pressure set by thrust chamber pressure plus chamber injector delta pressure
  - Chamber heat transfer limits turbine available energy
  - Turbine flow does not affect engine specific impulse

ROCKET ENGINE CYCLE



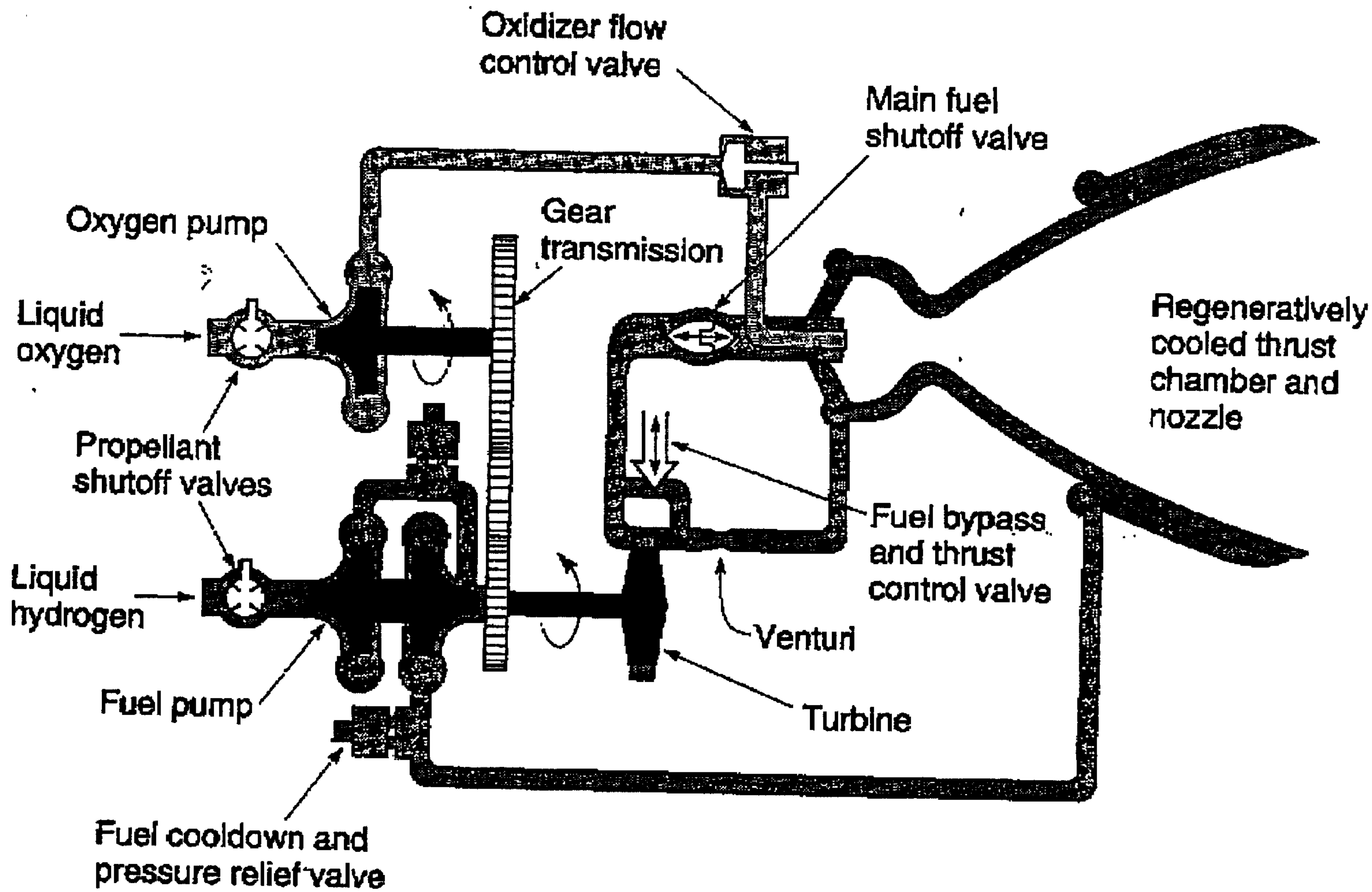


FIGURE 6–11. Schematic flow diagram of the RL10B-2 upper stage rocket engine. For data see Table 8–1. (Courtesy of Pratt & Whitney, a division of United Technologies.)

ROCKET ENGINE CYCLES

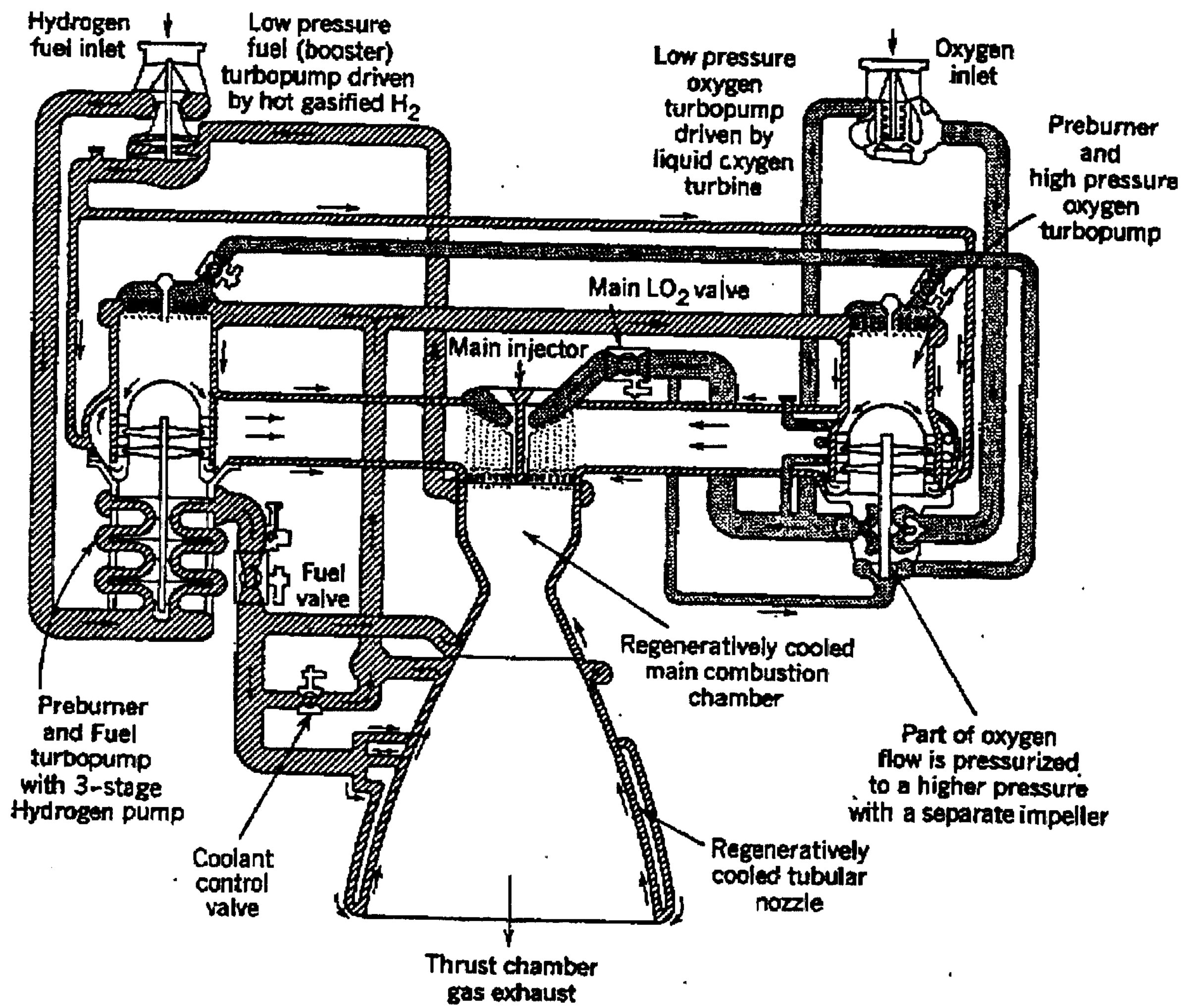
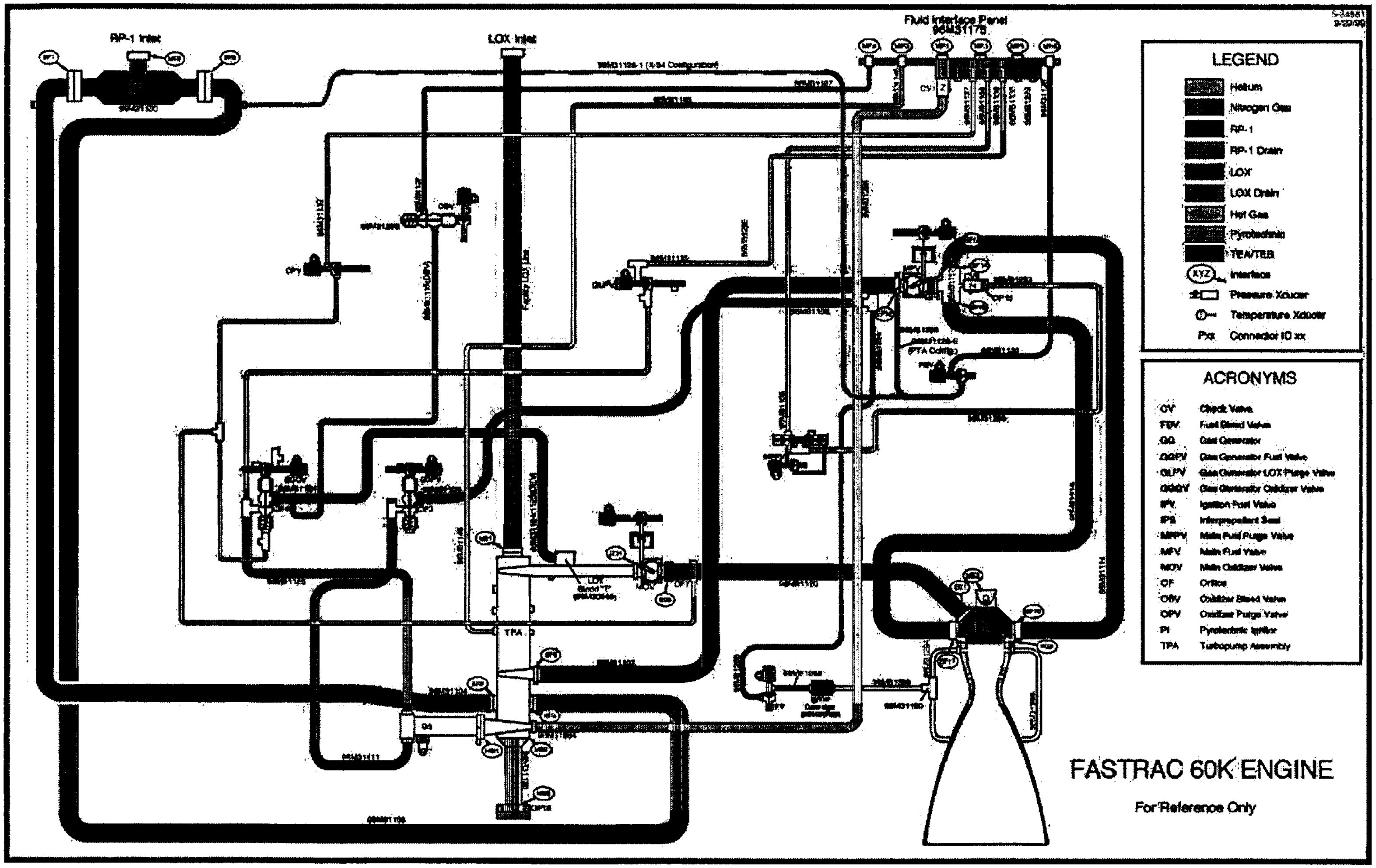


FIGURE 6–12. Flow diagram for the staged combustion cycle of the Space Shuttle Main Engine (SSME) using liquid oxygen and a liquid hydrocarbon fuel. (Courtesy of The Boeing Company, Rocketdyne Propulsion and Power.)

ROCKET ENGINE CYCLES



FASTRAC ENGINE

ROCKET ENGINE CYCLES

- **Propellant type and combination significantly impact turbopump design**

Propellant	Liquid Fluorine	Hydrazine	Liquid Hydrogen	Methane	Monomethyl-hydrazine
Chemical formula	F_2	N_2H_4	H_2	CH_4	CH_3NHNH_2
Molecular mass	38.0	32.05	2.016	16.03	46.072
Melting or freezing point (K)	53.54	274.69	14.0	90.5	220.7
Boiling point (K)	85.02	386.66	20.4	111.6	360.6
Heat of vaporization (kJ/kg)	166.26[b]	44.7[b] (298.15 K)	446	510[b]	875
Specific heat (kcal/kg-K)	0.368 (85 K)	0.736 (293 K)	1.75[b] (20.4 K)	0.835[b]	0.698 (293 K)
	0.357 (69.3 K)	0.758 (338 K)	—		0.735 (393 K)
Specific gravity[c]	1.636 (66 K)	1.005 (293 K)	0.071 (20.4 K)	0.424 (111.5 K)	0.8788 (293 K)
	1.440 (93 K)	0.952 (350 K)	0.076 (14 K)		0.857 (311 K)
Viscosity (centipoise)	0.305 (77.6 K)	0.97 (298 K)	0.024 (14.3 K)	0.12 (111.6 K)	0.855 (293 K)
	0.397 (70 K)	0.913 (330 K)	0.013 (20.4 K)	0.22 (90.5 K)	0.40 (344 K)
Vapor pressure (MPa)	0.0087 (100 K)	0.0014 (293 K)	0.2026 (23 K)	0.033 (100 K)	0.0073 (300 K)
	0.00012 (66.5 K)	0.016 (340 K)	0.87 (30 K)	0.101 (117 K)	0.638 (428 K)

ROCKET ENGINE CYCLES

- **Propellant type and combination significantly impact turbopump design**

Nitric Acid[a] (99%) pure)	Nitrogen Tetroxide	Liquid Oxygen	Rocket Fuel RP-1	Unsymmetrical Dimethyl-hydrazine (UDMH)	Water
HNO_3	N_2O_4	O_2	Hydrocarbon $CH_{1.97}$	$(CH_3)_2NNH_2$	H_2O
63.016	92.016	32.00	~ 175	60.10	18.02
231.6	261.95	54.4	225	216	273.15
355.7	294.3	90.0	460–540	336	373.15
480	413[b]	213	246[b]	542 (298 K)	2253[b]
0.042 (311 K)	0.374 (290 K)	0.4 (65 K)	0.45 (298 K)	0.672 (298 K)	1.008 (273.15 K)
0.163 (373 K)	0.447 (360 K)			0.71 (340 K)	
1.549 (273.15 K)	1.447 (293 K)	1.14 (90.4 K)	0.58 (422 K)	0.856 (228 K)	1.002 (373.15 K)
1.476 (313.15 K)	1.38 (322 K)	1.23 (77.6 K)	0.807 (289 K)	0.784 (244 K)	1.00 (293.4 K)
1.45 (273 K)	0.47 (293 K)	0.87 (53.7 K)	0.75 (289 K)	4.4 (220 K)	0.284 (373.15 K)
	0.33 (315 K)	0.19 (90. 4 K)	0.21 (366 K)	0.48 (300 K)	1.000 (277 K)
0.0027 (273.15 K)	0.01014 (293 K)	0.0052 (88.7 K)	0.002 (344 K)	0.0384 (289 K)	0.00689 (312 K)
0.605 (343 K)	0.2013 (328 K)		0.023 (422 K)	0.1093 (339 K)	0.03447 (345 K)

ROCKET ENGINE CYLCES

Table 6-2 Operating parameters for turbopumps on the SSME at rated power level.

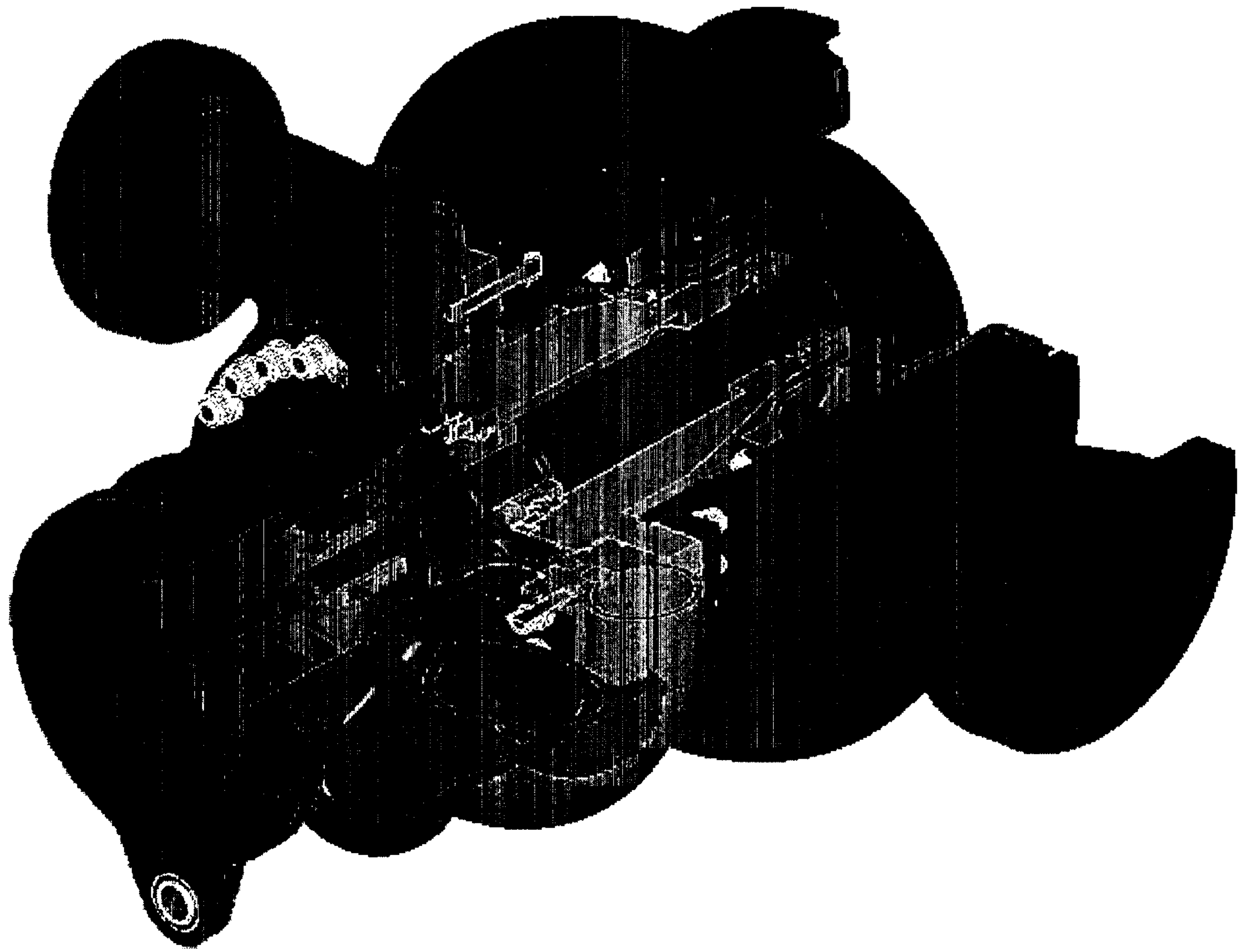
Turbopump Figure Reference	LPOTP 6-7	HPFTP 6-5	HPOTP Main 6-18	HPOTP Boost
Pump:				
Fluid	LOX	LH_2	LOX	LOX
Inlet density, lb/ft^3	71.03	4.32	70.28	70.28
Total inlet pressure, psia	100.0	250	374.8	4,031
Total discharge pressure, psia	408.8	6,024.8	4,129.8	6,952.2
Pump developed head, ft	625.9	168,920	7,591	5,934
Flow rate, lb/s	890.3	148.5	1,067	101.2
Volumetric flow at inlet, gpm	5,626	15,436	6,814	594.7
Shaft speed, rpm	4,961	33,974	27,039	27,039
Efficiency, %	68.6	77.3	67.3	82.5
Shaft power, bhp	1,476	58,970	21,882	1,330
Turbine[a] **:**				
Fluid	LOX	Hot gas	Hot gas	
Inlet total pressure, psia	3.961	4,933	4,924	
Discharge total pressure, psia	408.8	3,376	3,286	
Isentropic velocity ratio	0.465	0.356	0.286	
Pressure ratio, T-T	--	1.461	1.498	
Inlet temperature, °R	191.3	1835.9	1430	
Discharge temperature, °R	189.7	1698.3	1314.9	
Flow rate, lb/s	176.9	145.6	60.6	
Horsepower	1,476	58,972	23,212	
Shaft speed, rpm	4,961	33,974	27,039	
Efficiency, %	63.1	79.6	78.1	

[a]The turbine for the LPOTP is a hydraulic turbine, and the two high-pressure turbines are two-stage pressure compounded designs using O_2-LH_2 combustion products.

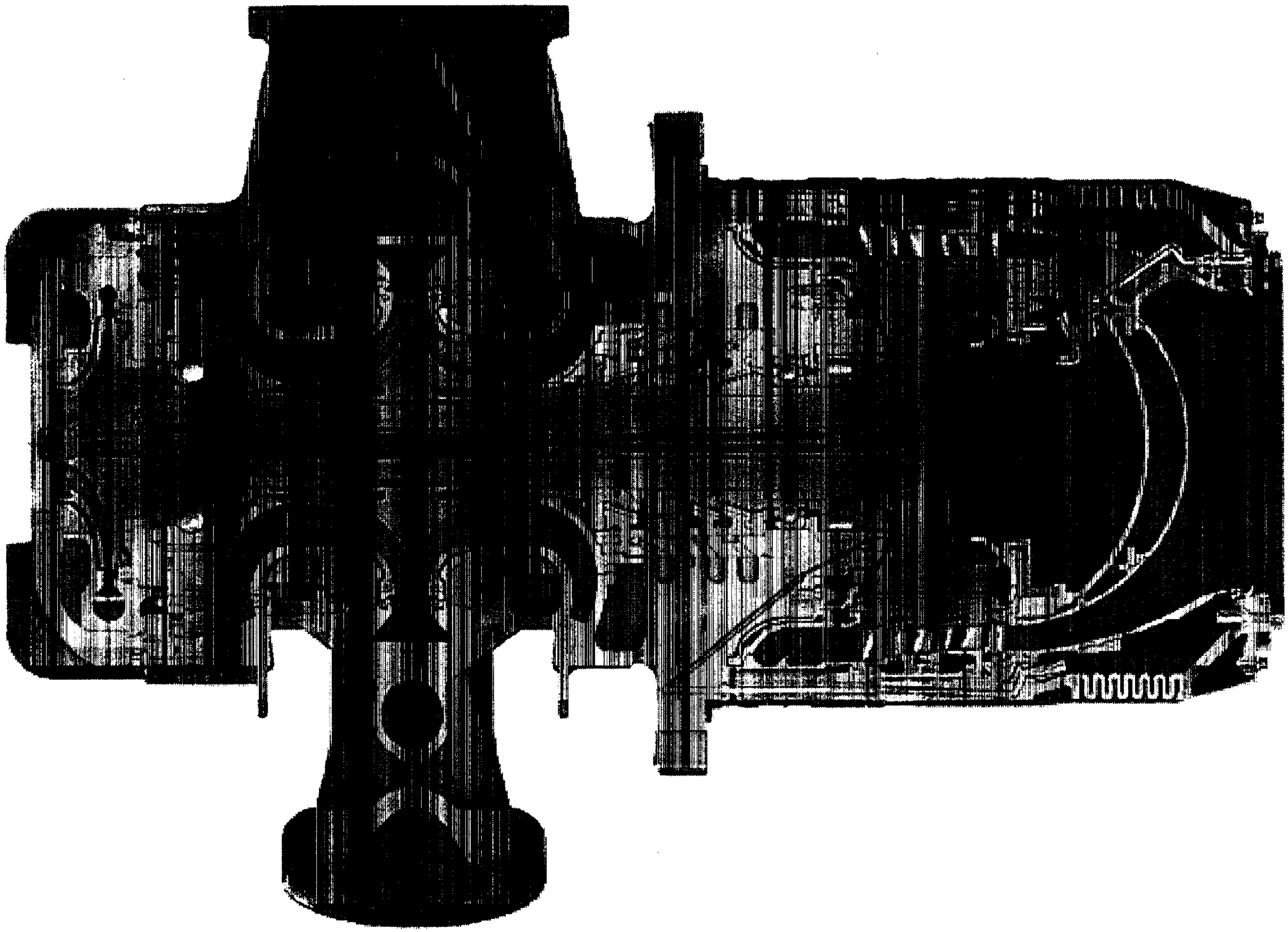
ROCKET ENGINE CYCLES

- Other engine driven requirements
  - Envelope
    - Space/Volume allocation
    - Inlet and outlet locations
  - Weight allocation
  - Life
    - Number of cycles
    - Total time
  - Sea Level and/or altitude start
    - Propellant conditioning
  - Cost

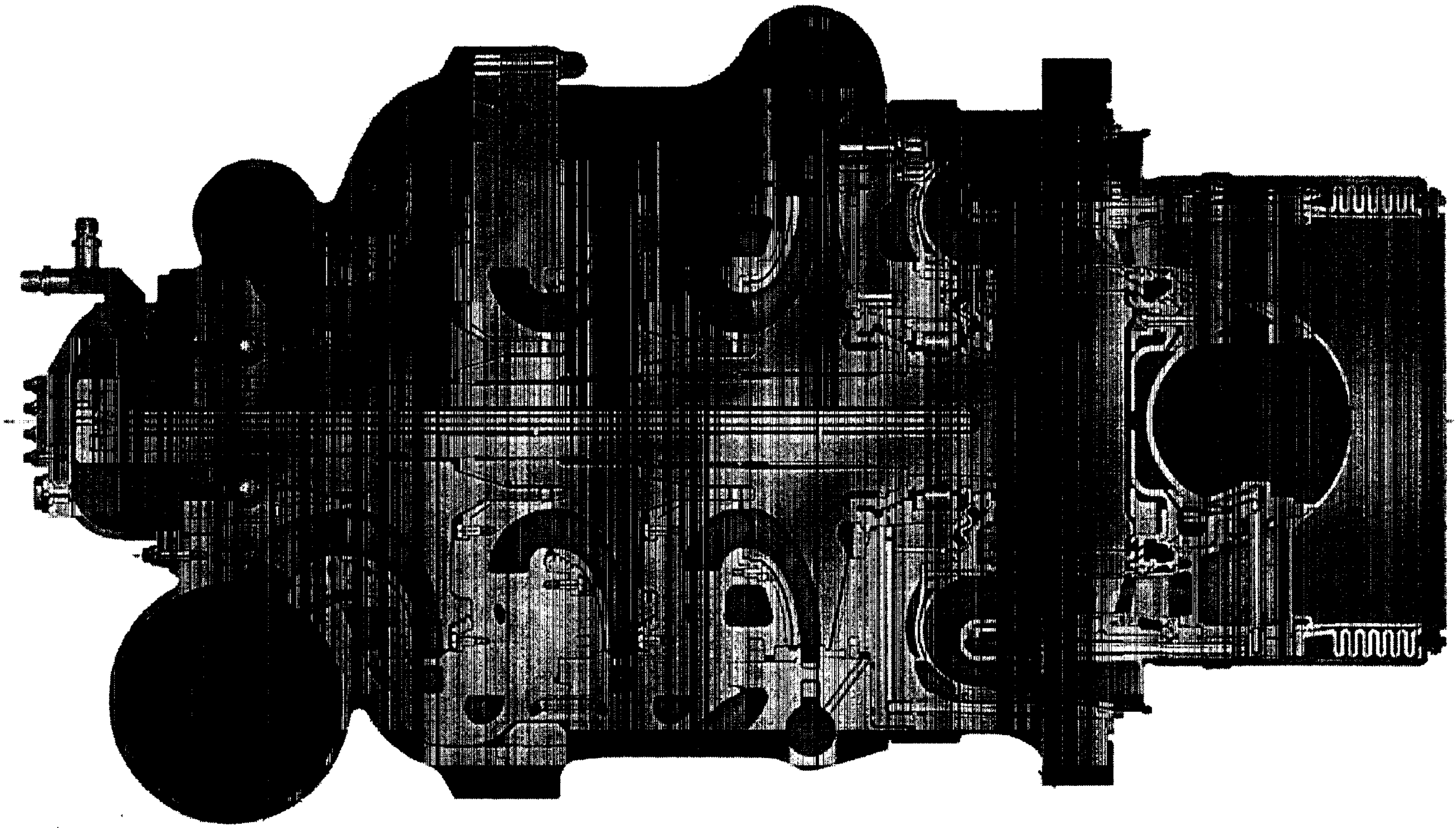
ROCKET ENGINE TURBOPUMPS



ROCKET ENGINE TURBOPUMPS



ROCKET ENGINE TURBOPUMPS



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TURBOPUMP BEARINGS

- Bearings perform three primary functions
  - Radial control of the rotor
    - Prevent rubs
    - Maintain radial clearance to reduce parasitic flow losses
  - Axial control of the rotor
    - Maintain control of the rotor during transients
      - Pressure and thermal loads
    - React residual axial thrust loads during mainstage
  - Control of rotordynamics
    - Provide adequate radial stiffness
    - Provide damping

TURBOPUMP BEARINGS

- Harsh operating environment
  - Bearings usually cooled by the pumped fluid
  - Pumped fluid provides little of no lubrication
  - High operating speeds
  - Can be exposed to high transient radial and axial loads
- Two major bearing types used in turbopumps
  - Rolling element
  - Fluid film

TURBOPUMP BEARINGS

- Rolling element bearings
  - Most commonly used bearing
  - High direct stiffness
  - Minimum damping
  - Minimum cross–coupling
  - Wear and fatigue common failure mode, limit life
  - Can limit maximum operating speed

TURBOPUMP BEARINGS

- Fluid film bearings
  - Hydrostatic bearing has potential benefits in rocket engine applications
    - Long life
    - Have desirable rotordynamic characteristics
      - Stiffness and damping
    - Do not limit shaft speed
    - Transient rubs during start and shutdown have to be controlled
      - Rub tolerant materials needed
      - Hybrid design that uses rolling elements during transients

ROLLING ELEMENT BEARINGS

Type of Bearing	Advantages	Disadvantages	Primary condition for use
Conrad-type ball	Any combination of radial and thrust direction; large misalignment capability; moment-load capacity	Limited number of balls; two-piece cage necessary	Combined load; two-direction thrust loads
Angular-Contact ball	Thirty percent more capacity than similar-size Conrad; one-piece cage	Predominant thrust required; one-direction capacity; lower misalignment tolerances than Conrad	High speed, high-load single-direction thrust; can be used in duplex pairs for two-direction thrust
Split-ring	Thirty percent more thrust capacity than similar-size Conrad; one-piece cage; two-direction thrust capability; lower axial clearance through use of Gothic arch	Predominant thrust required; lower misalignment tolerance than Conrad	Two-direction thrust
Cylindrical	Much higher radial capacity than ball bearing; provides axial freedom of shaft; higher radial stiffness than ball bearings; one-piece cage	No axial load capacity; roller ends wear in nonlubricating coolants; lower misalignment tolerance than ball bearings; requires negative internal clearance	High radial capacity without axial restraint; higher radial stiffness

TURBOPUMP BEARING

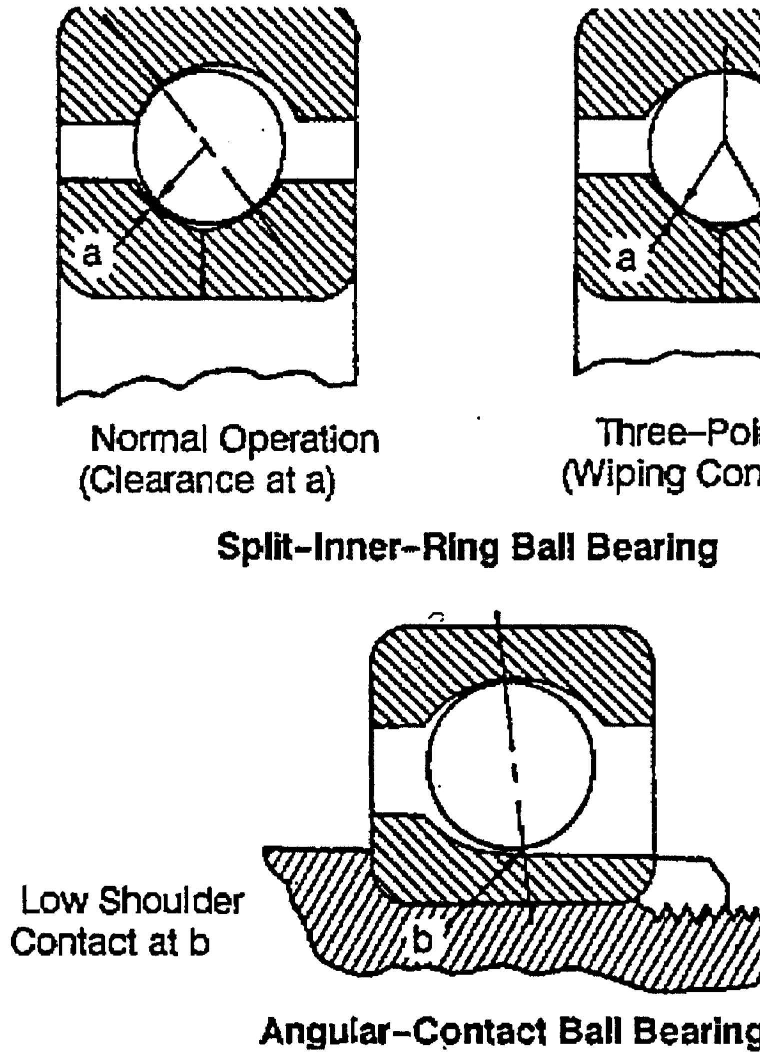
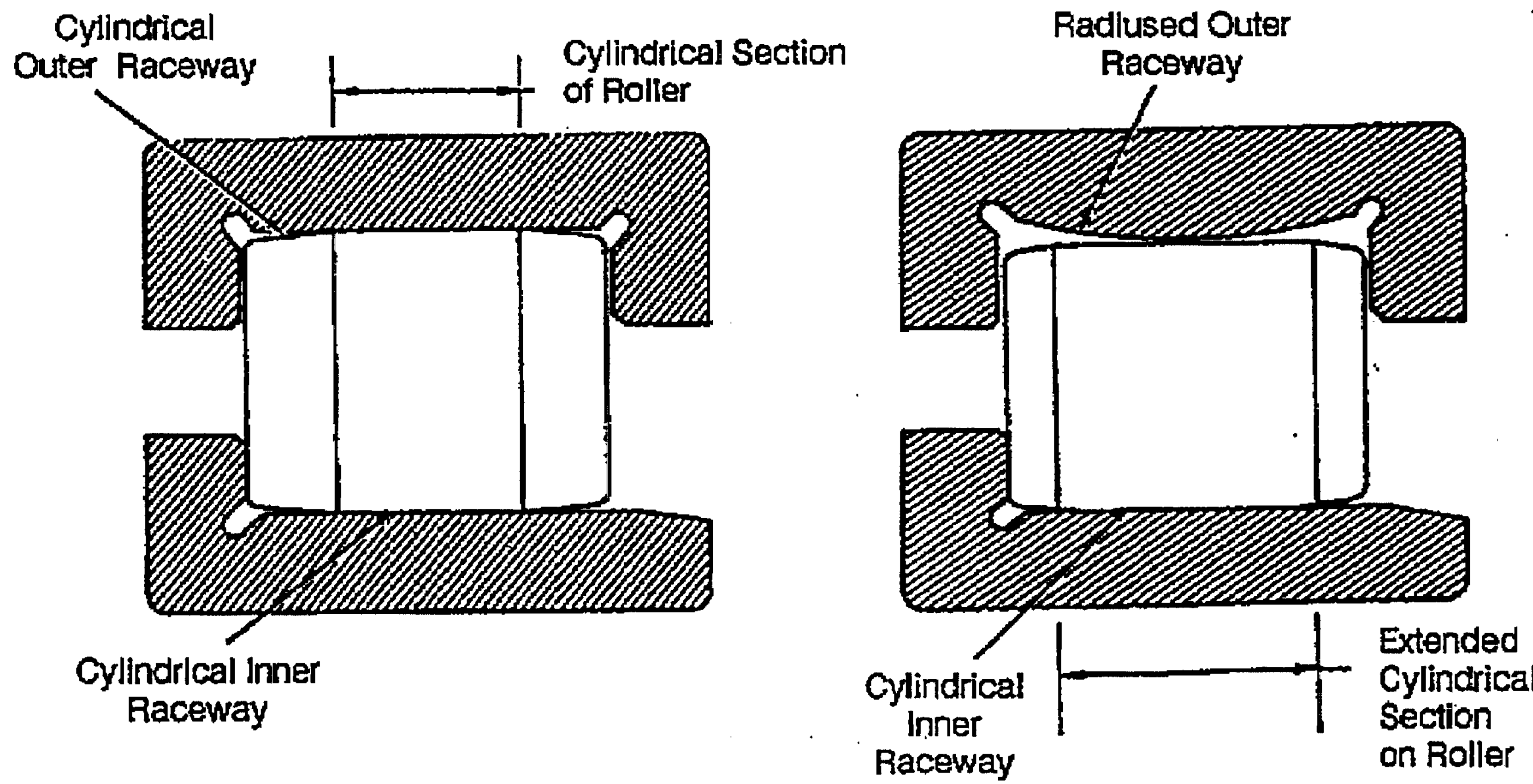


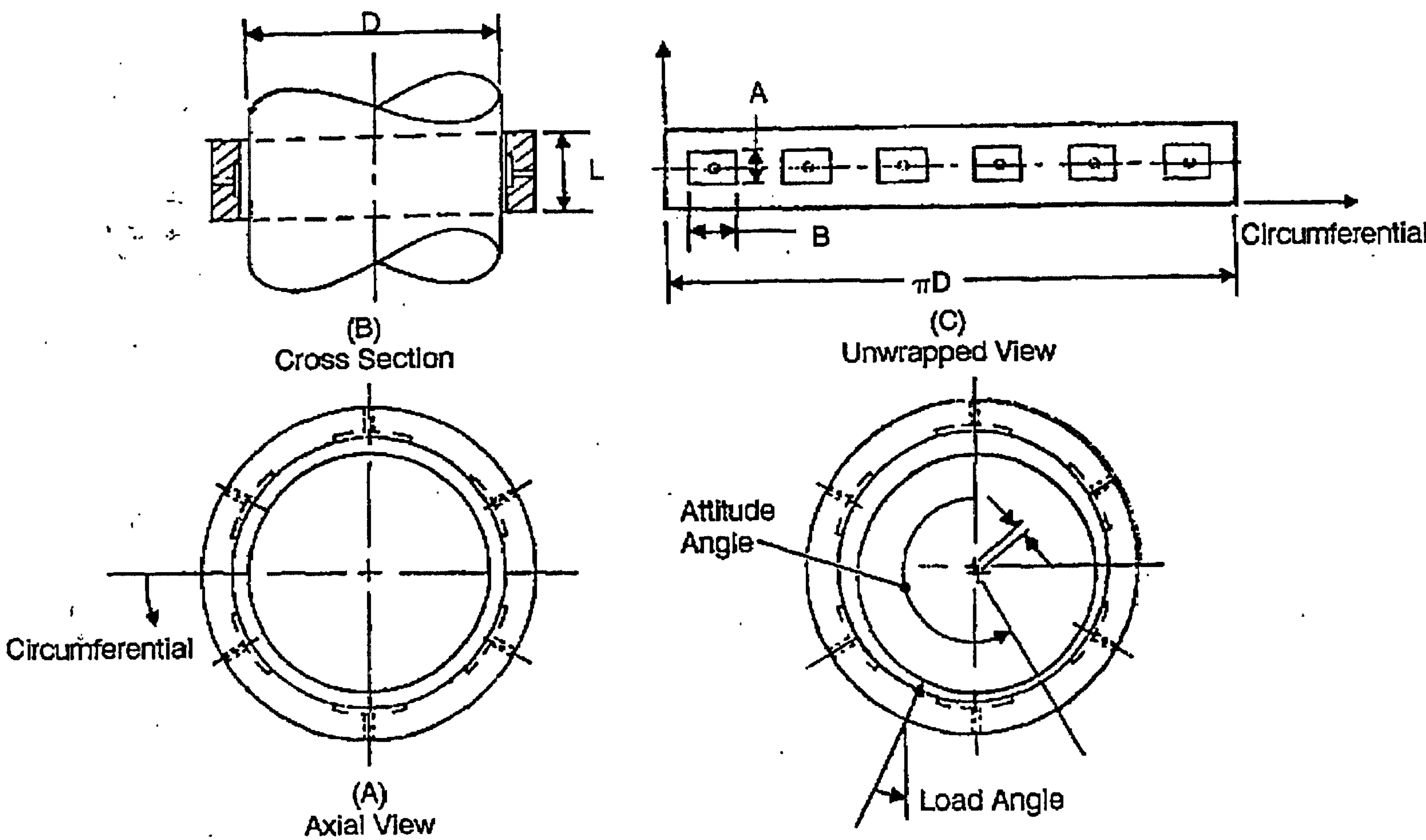
Fig. 6-66 Typical ball-bearing designs.

TURBOPUMP BEARINGS



TYPICAL ROLLER BEARING DESIGNS

TURBOPUMP BEARINGS

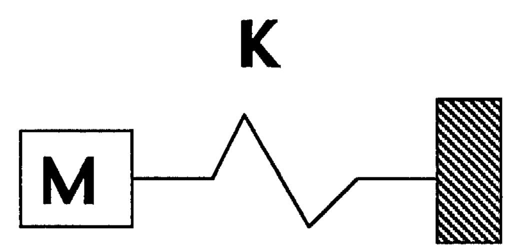


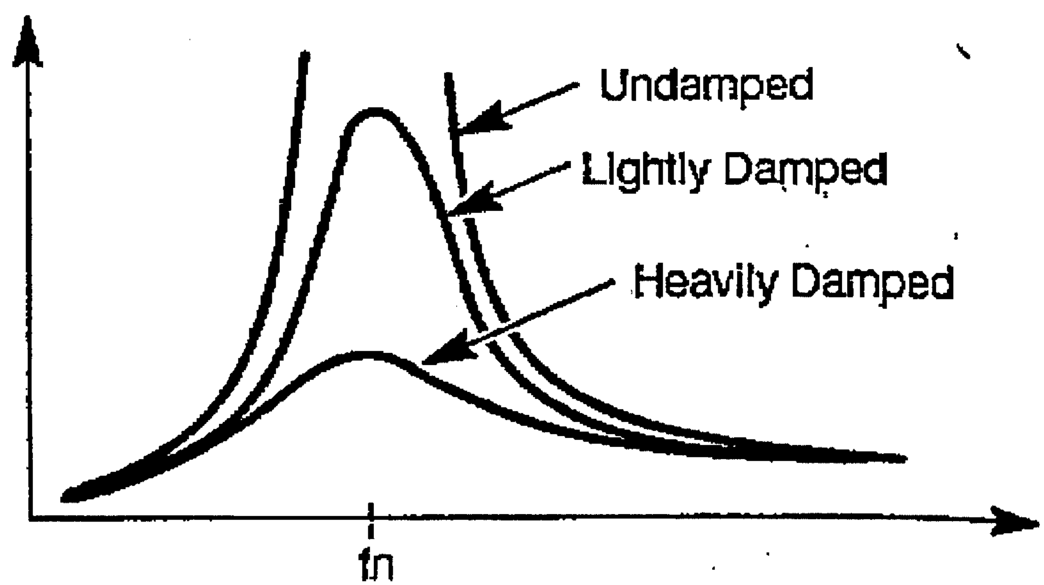
Typical Hydrostatic Bearing

TURBOPUMP ROTORDYNAMICS

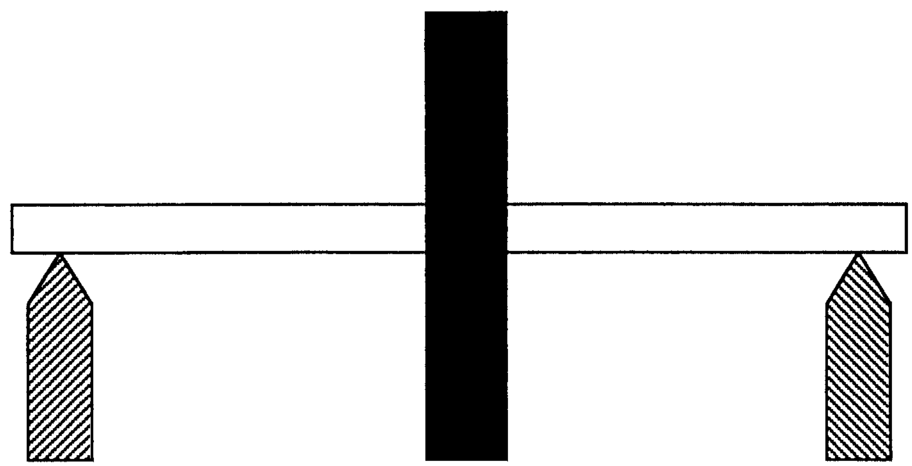
- **Simple system natural frequency**

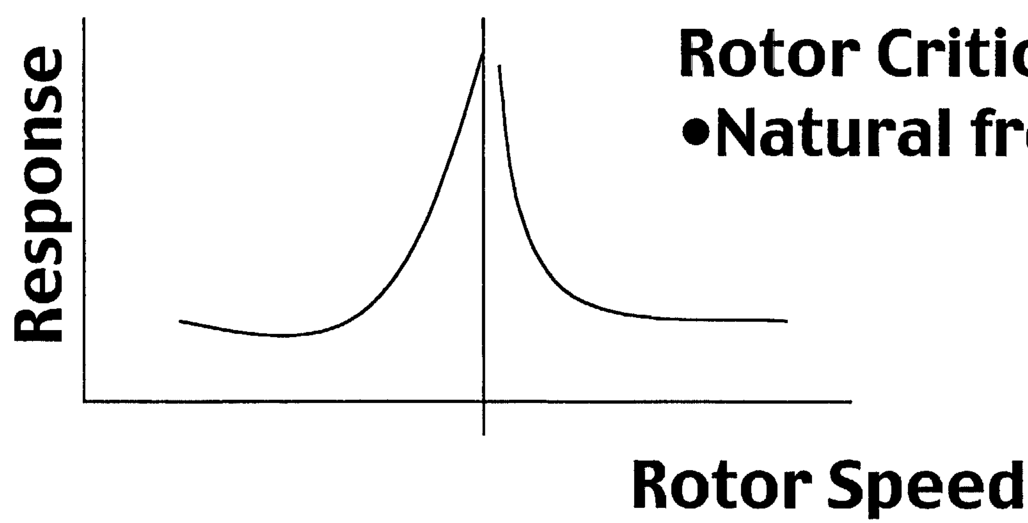
Natural Frequency
$f_n = (K/M)^{1/2}$





TURBOPUMP ROTORDYNAMICS





Rotor Critical Speed

- **Natural frequency = Rotor Spin Sp**

TURBOPUMP ROTORDYNAMICS

- Difference from simple spring mass system
  - Bearing stiffness and damping is speed dependent
  - X and Y motions are coupled
  - Rotor whirl can occur at nonsynchronous frequencies
  - Rotor whirl can be unstable
  - Gyroscopic effects

TURBOPUMP ROTORDYNAMICS

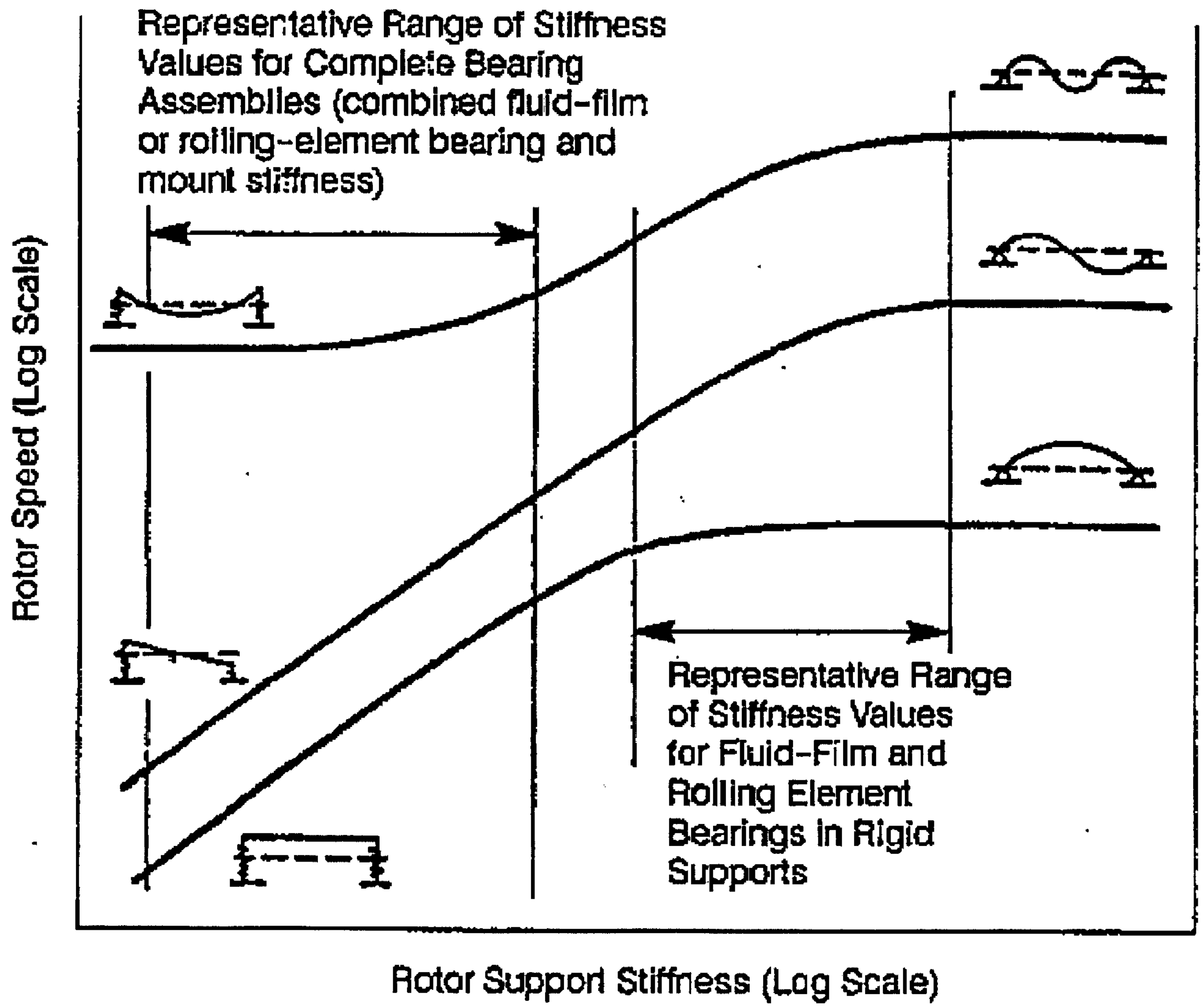
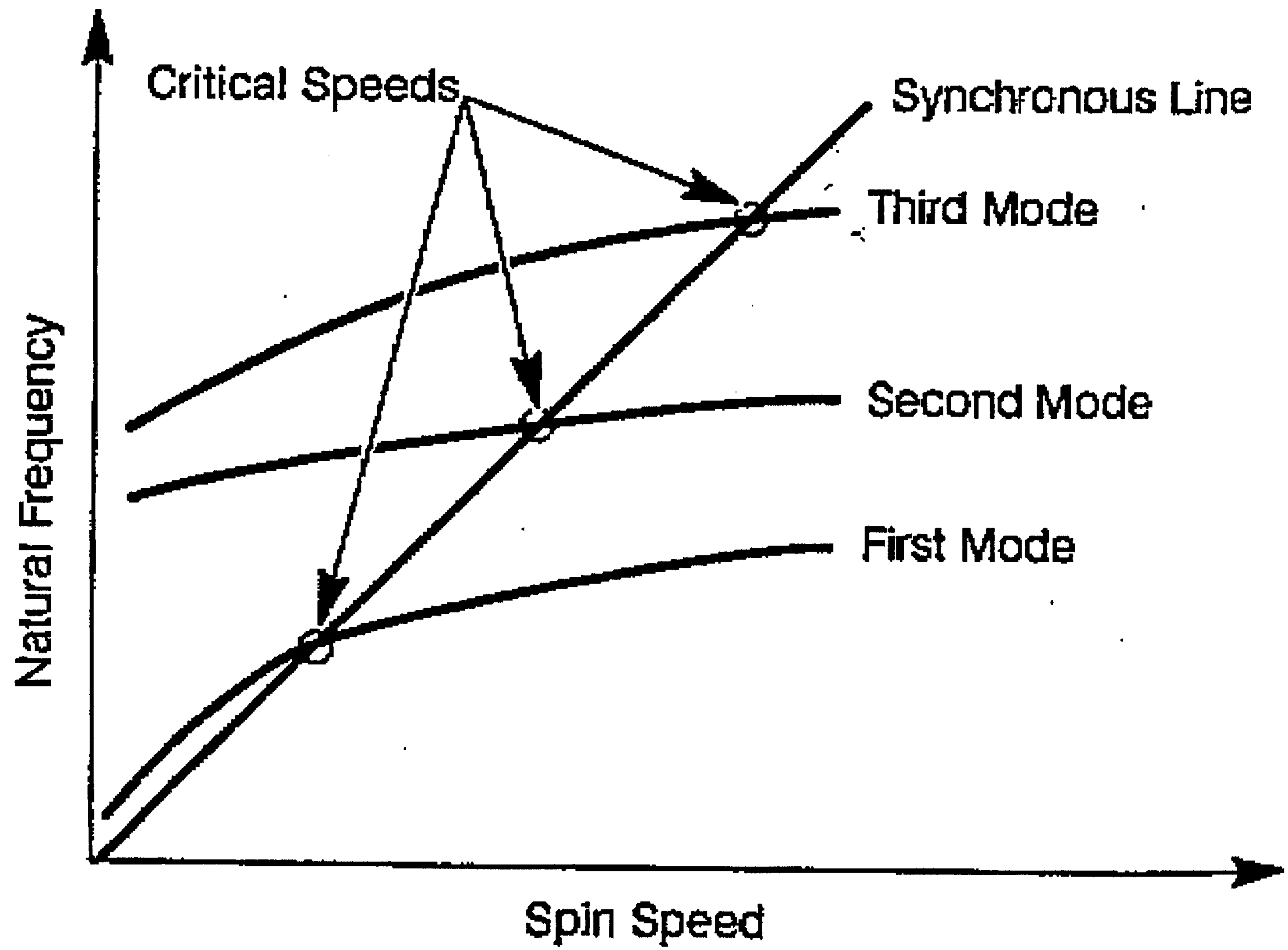


Fig. 6-62 Effect of rotor supports on critical speeds.

TURBOPUMP ROTORDYNAMICS



TURBOPUMP ROTORDYNAMICS

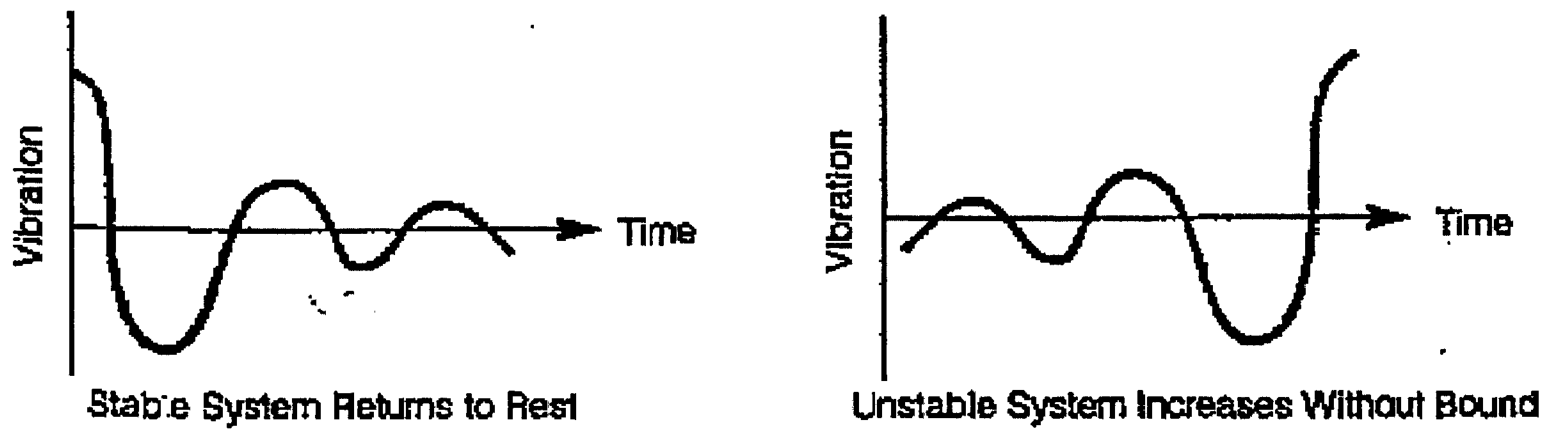


Fig. 6-64 Stability of a simple rotor system.

TURBOPUMP ROTORDYNAMICS

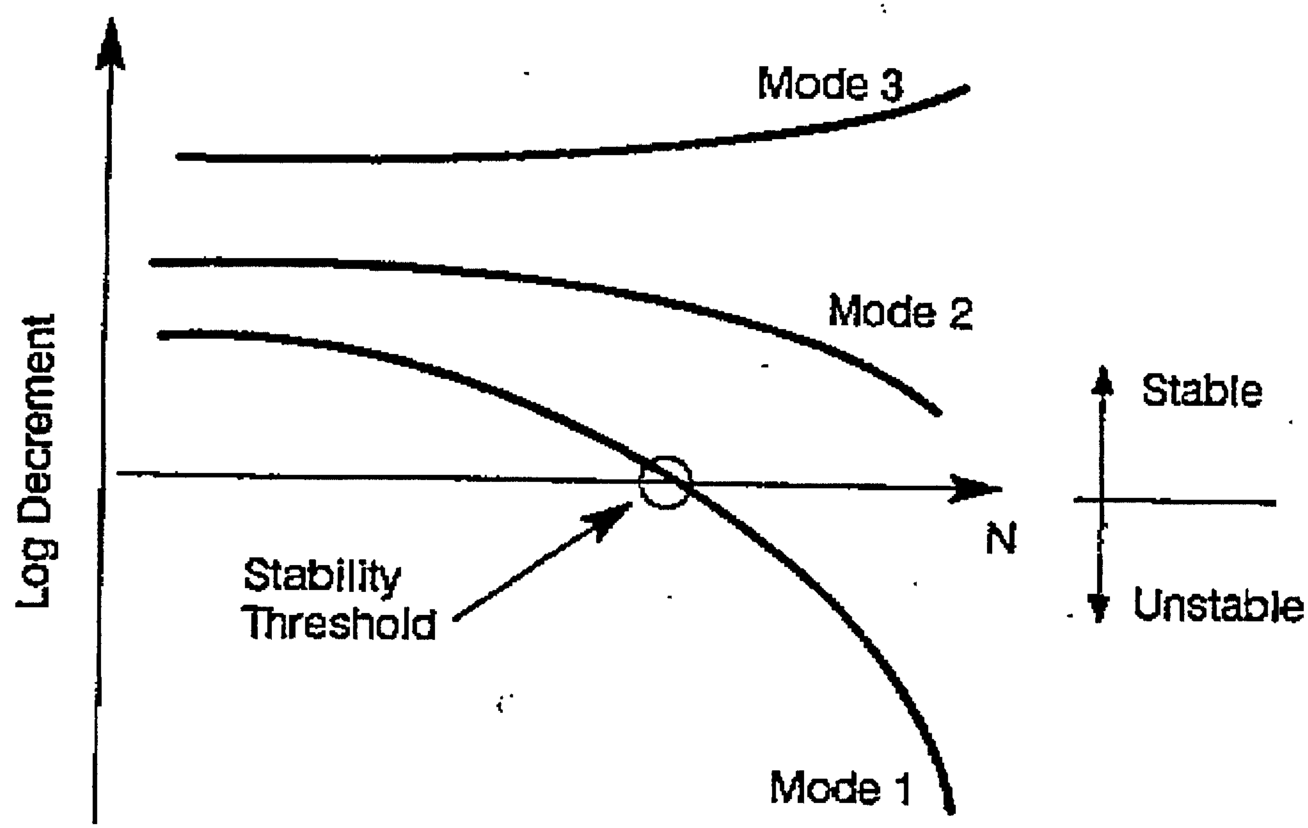


Fig. 6-65 Graphical representation of rotor stability.

TURBOPUMP DYNAMIC SEAL

- Dynamic seals are those between rotating and stationary parts
  - Required to minimize internal parasitic flows
  - Separate propellants
    - Fuel from oxidizer
- Seal failures can cause catastrophic turbopump failures
  - Propellant mixing internal to turbopump
  - Rubs in oxidizing environments
- Dynamic seals must not fail

TURBOPUMP DYNAMIC SEAL

- Dynamic Seal Types
  - Labyrinth
    - Close clearance seals
  - Face contacting
    - Axial contact between seal face and a mating ring on shaft
  - Shaft contacting
    - Radial contact between seal face and shaft
  - Floating ring seal
    - Utilize hydrostatic forces to maintain close clearance

TURBOPUMP DYNAMIC SEAL

- Dynamic Seal Types
  - Hydrodynamic face seals
    - Utilize hydrodynamic forces to maintain small clearances
- Relative leakage
  - Face contact — Minimum
  - Shaft contact — Minimum
  - Hydrostatic/Hydrodynamic — Low
  - Floating ring — Medium
  - Labyrinth — High

TURBOPUMP DYNAMIC SEAL

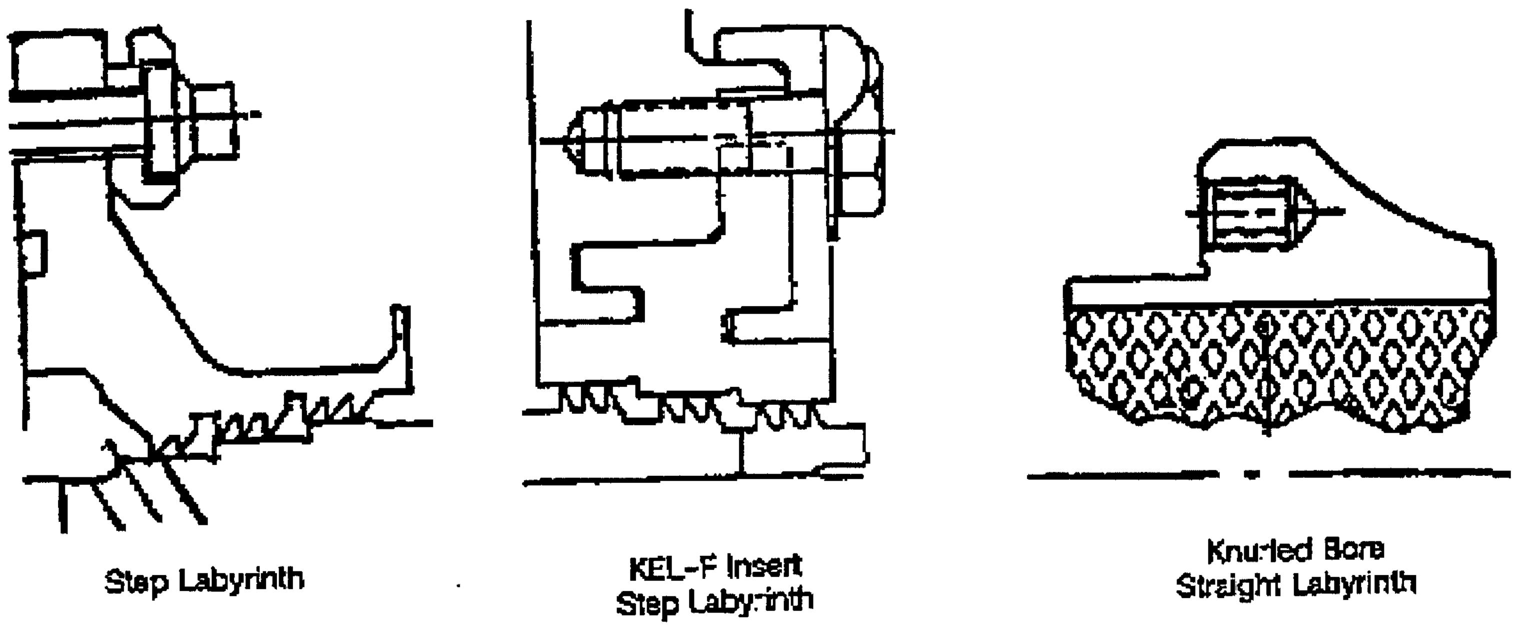
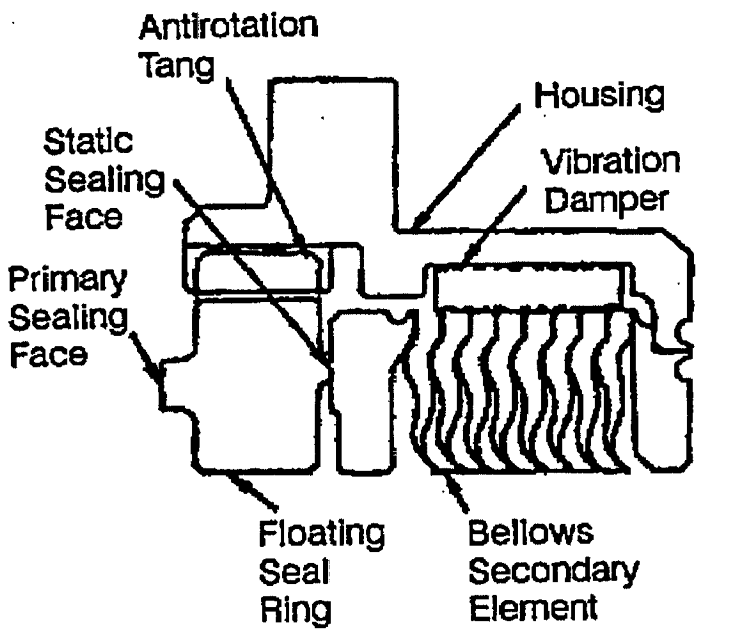
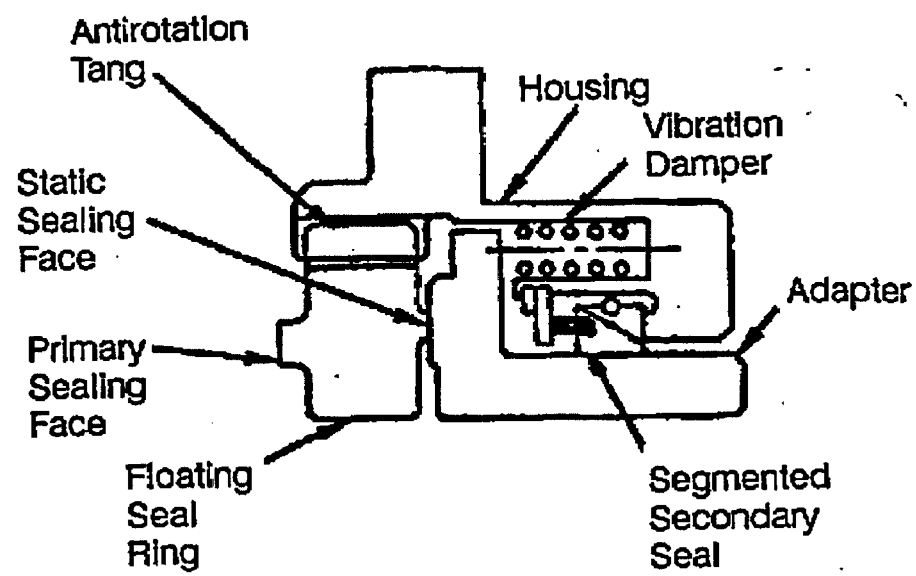


Fig. 6-76 Labyrinth-seal designs.

TURBOPUMP DYNAMIC SEAL



Face Contact Floating Seal Ring Bellows Secondary Element Seal



Face Contact Floating Seal Ring Segmented Secondary Seal

Fig. 6-70 Face contact seals.

TURBOPUMP DYNAMIC SEAL

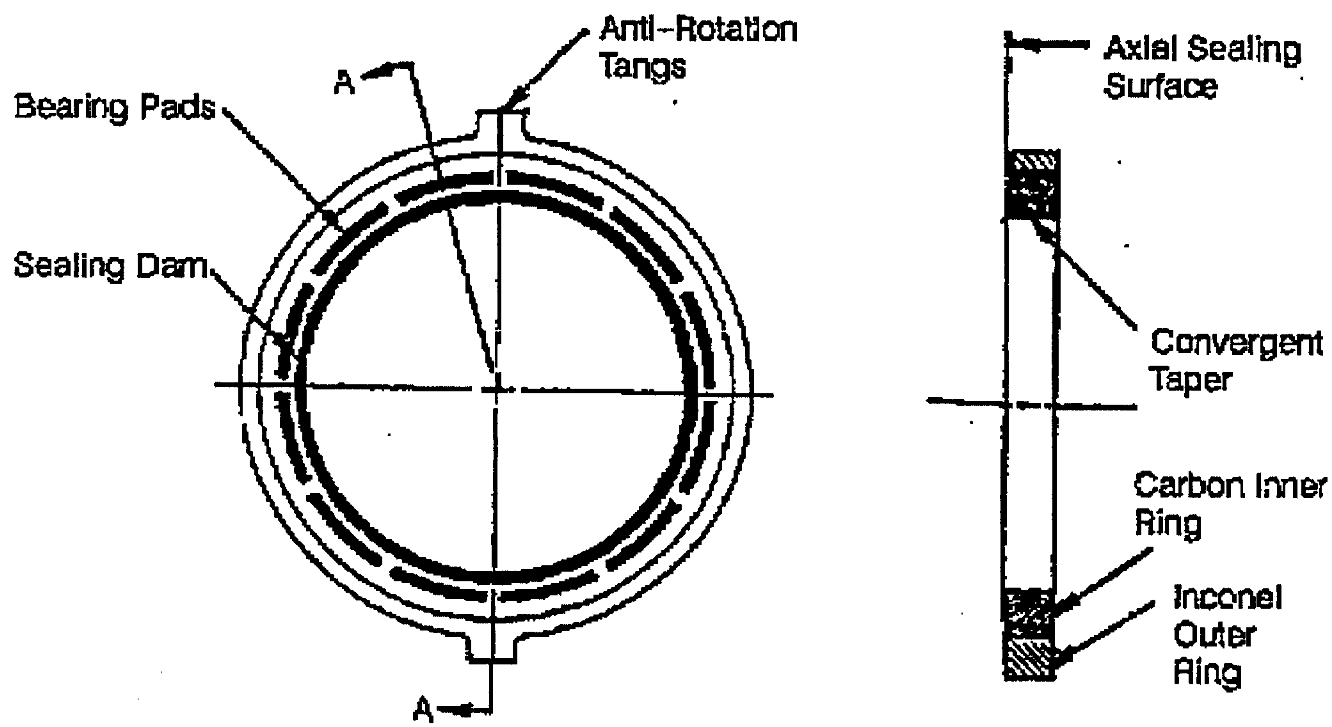


Fig. 6-72 Floating-ring seal.

TURBOPUMP DYNAMIC SEAL

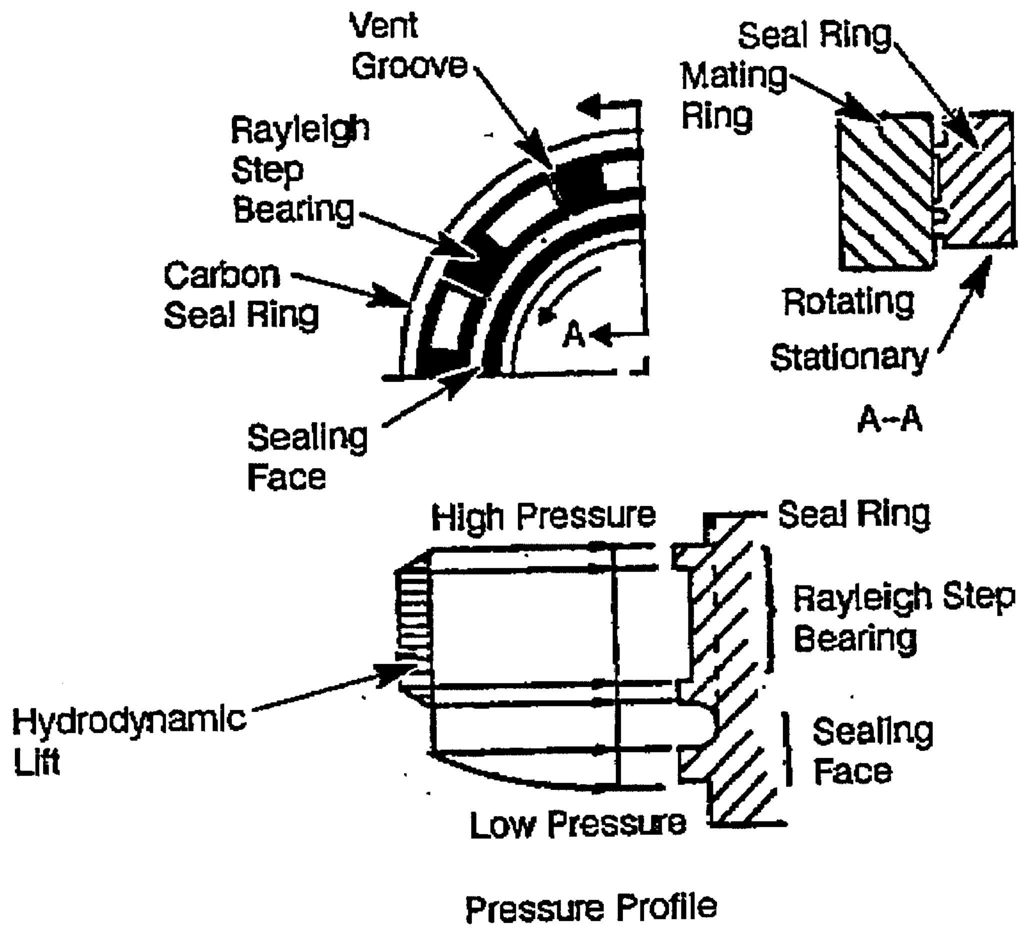


Fig. 6-74 Rayleigh-step hydrodynamic face seal.

TURBOPUMP DYNAMIC SEAL

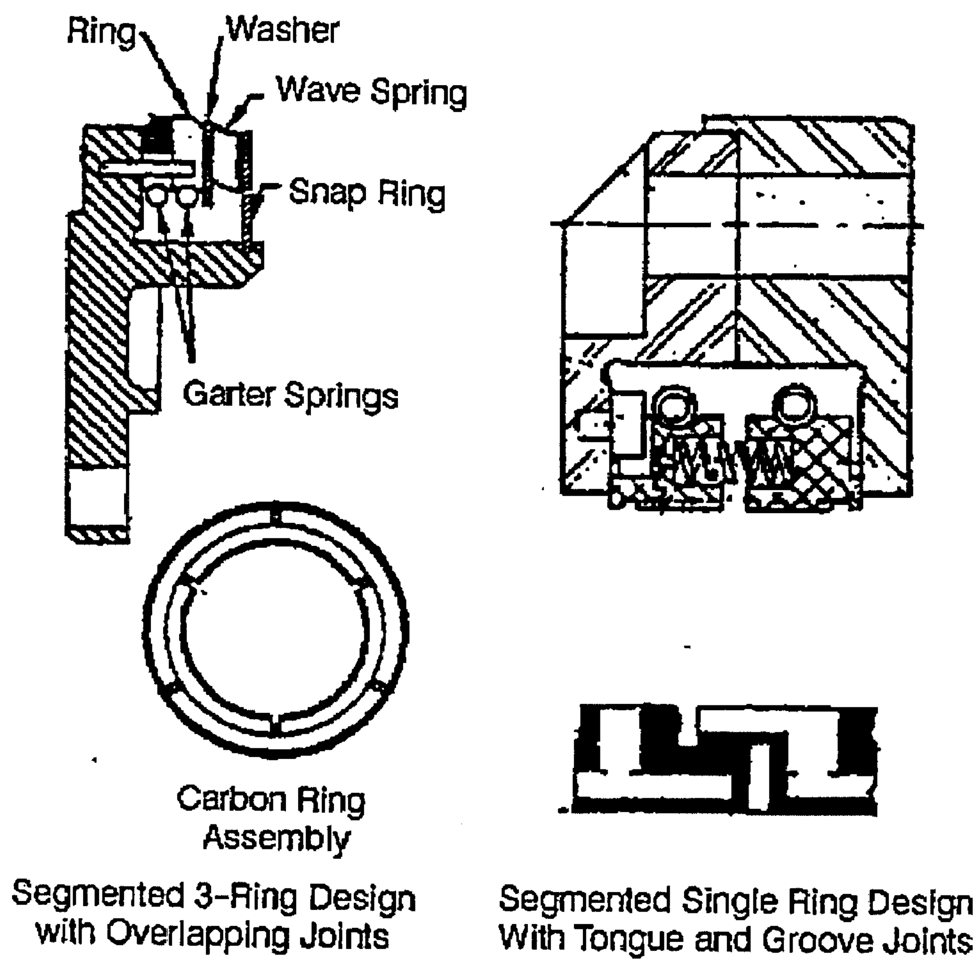


Fig. 6-71 Segmented shaft-riding seals.

TURBOPUMP DYNAMIC SEAL

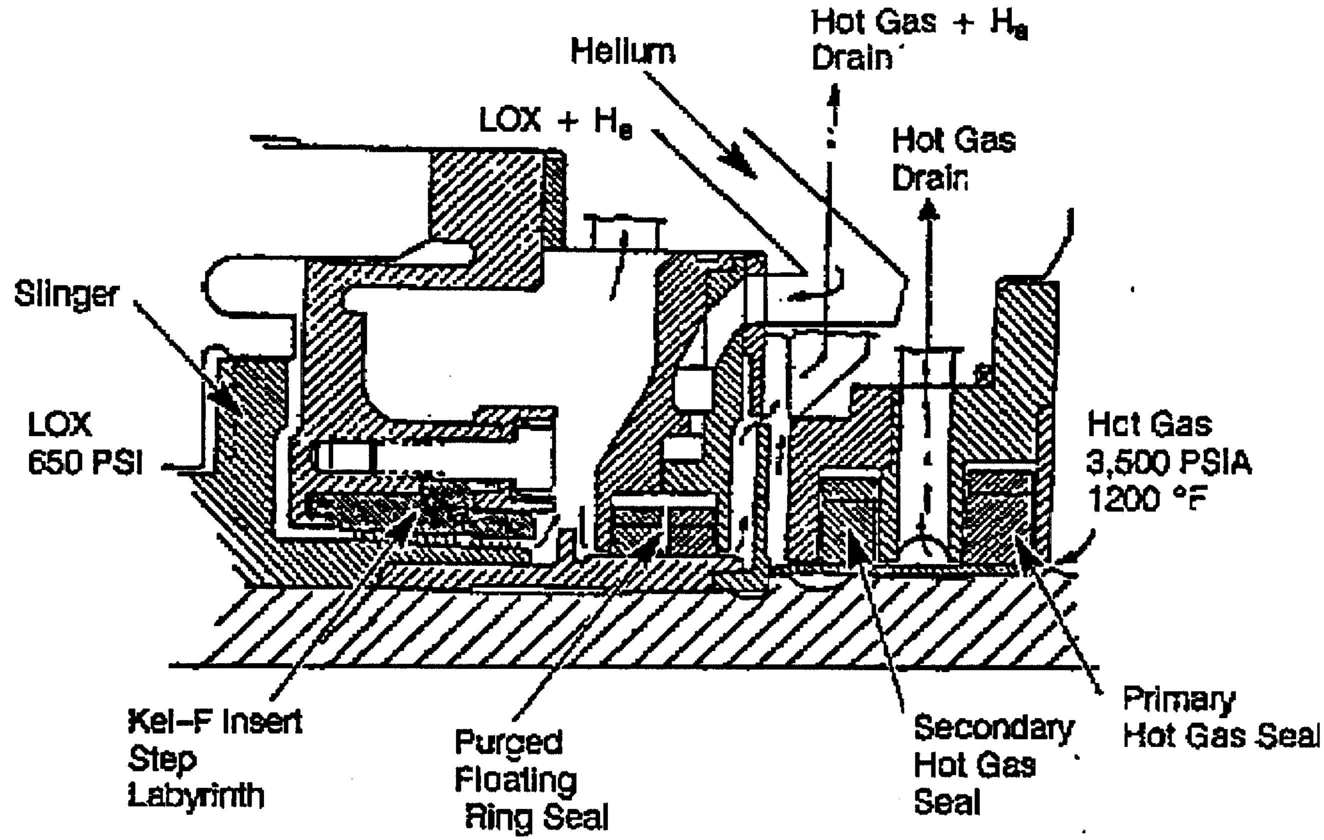


Fig. 6-78 Typical seal system for separating high-pressure propellants.

TURBOPUMP DYNAMIC SEALS

- Dynamic seals are critical and have challenging requirements
  - Non–lubricating fluids
  - Fluid compatibility issues
  - Large thermal gradients
  - Dynamic loads can be high
    - Fluid induced
    - Mechanically induced
  - High Pressures

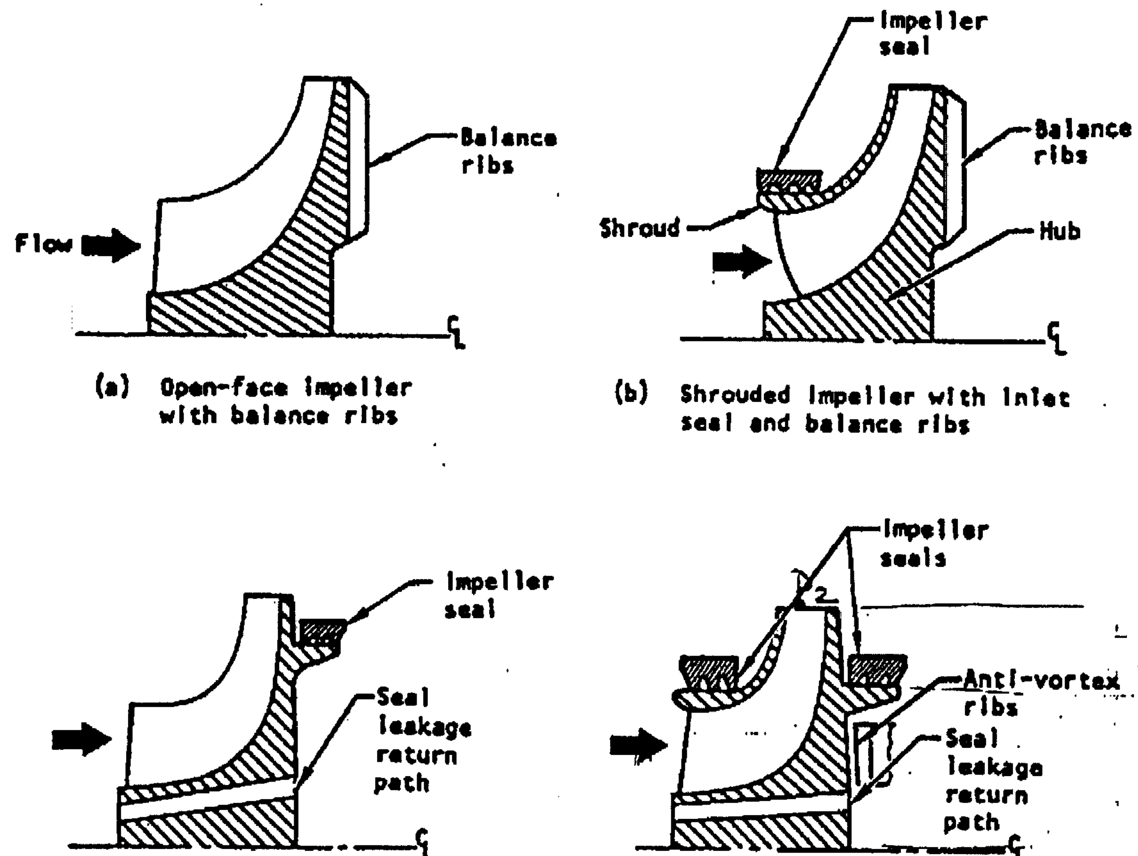
TURBOPUMP AXIAL THRUST BALANCE

- Delta pressures and axial momentum changes produce large axial forces on rotating elements
  - These axial forces must be managed so that bearings are not exposed to excessive axial loads
  - Two approache~~d~~s can be used
    - Reduce the residual axial force such that is less than the axial load capacity of the bearing
    - Use a balance piston to react the residual axial load
- Most high power density turbomachines require a balance piston

TURBOPUMP AXIAL THRUST BALANCE

- Several techniques are available to manage axial thrust loads
  - Locate seals to minimize force
  - Use rotating and/or stationary ribs to manage radial pressure profiles between rotating and stationary elements.
  - Arrange rotating elements so that forces counteract each other

TURBOPUMP AXIAL THRUST BALANCE



(a) Open-face impeller with balance ribs

(b) Shrouded impeller with inlet seal and balance ribs

(c) Open-face impeller with hub seal

(d) Shrouded impeller with inlet and hub seals and anti-vortex ribs

TURBOPUMP AXIAL THRUST BALANCE

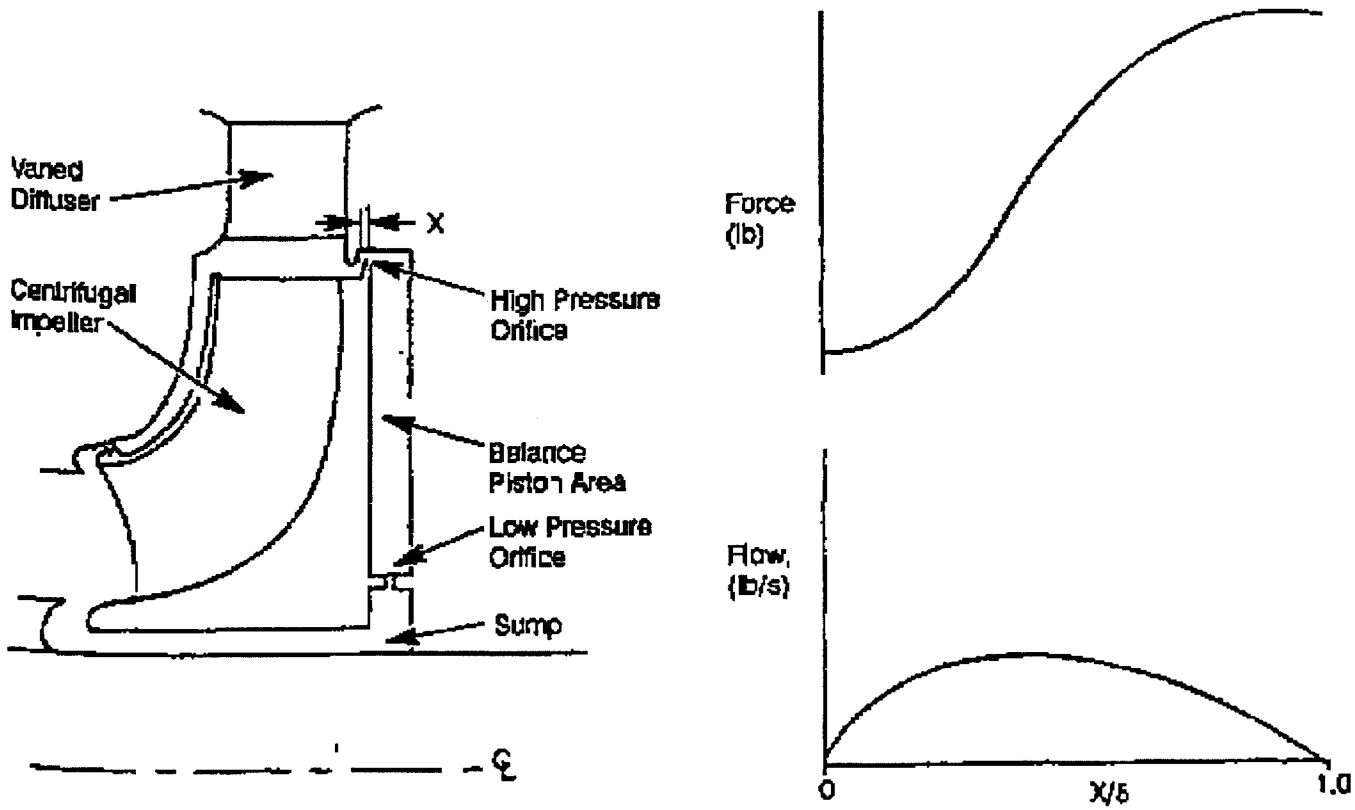
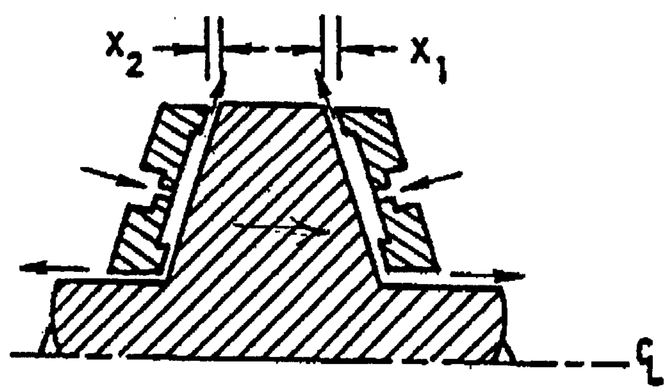
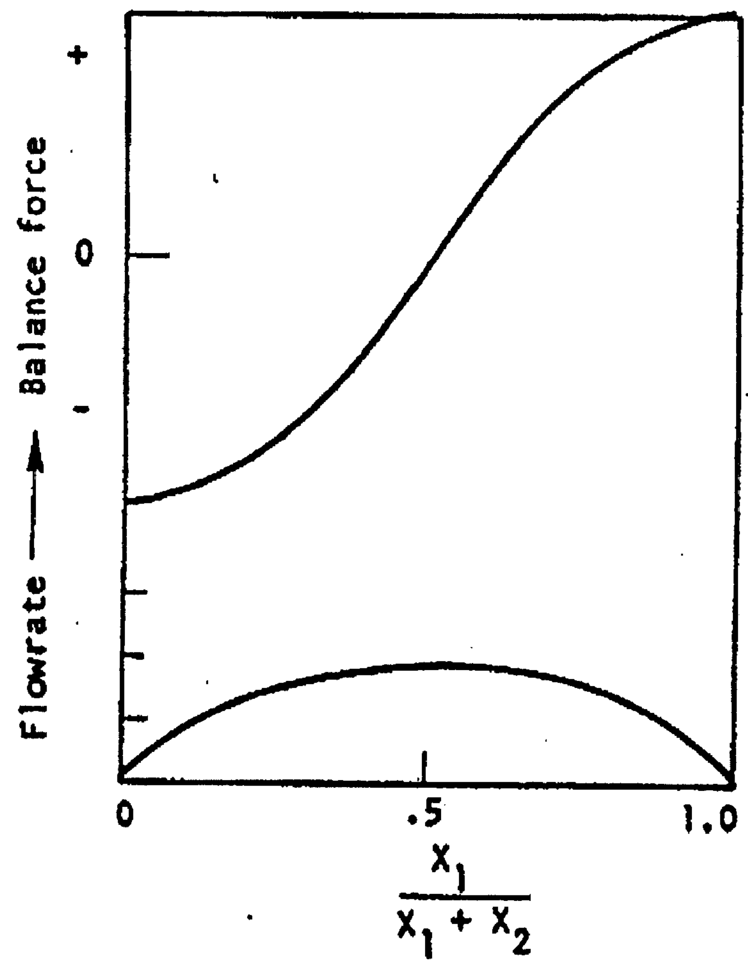


Fig. 6-45 Balance-piston concept.

TURBOPUMP AXIAL THRUST BALANCE

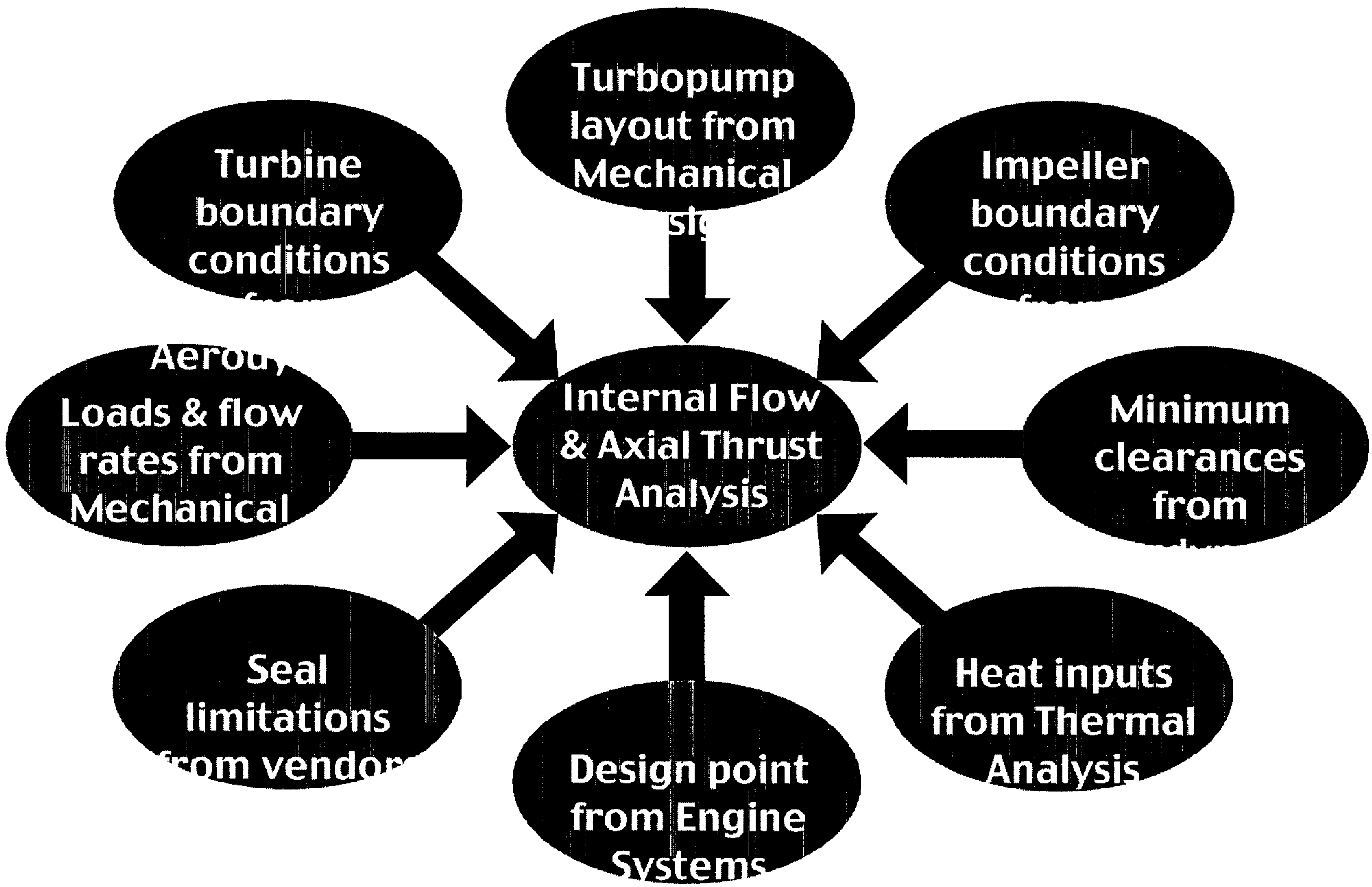




TURBOPUMP AXIAL THRUST BALANCE

- In high pressure and/or large machines axial forces can be in excess of 100,000 lb_f
  - Calculation of internal flows and resulting pressures and pressure profiles is a real challenge
  - Requires a thorough understanding of flow path geometry
    - Flow path geometry is a function of turbopump operating condition and deflections resulting from thermal and pressure loads

ANALYTICAL INTERFACES



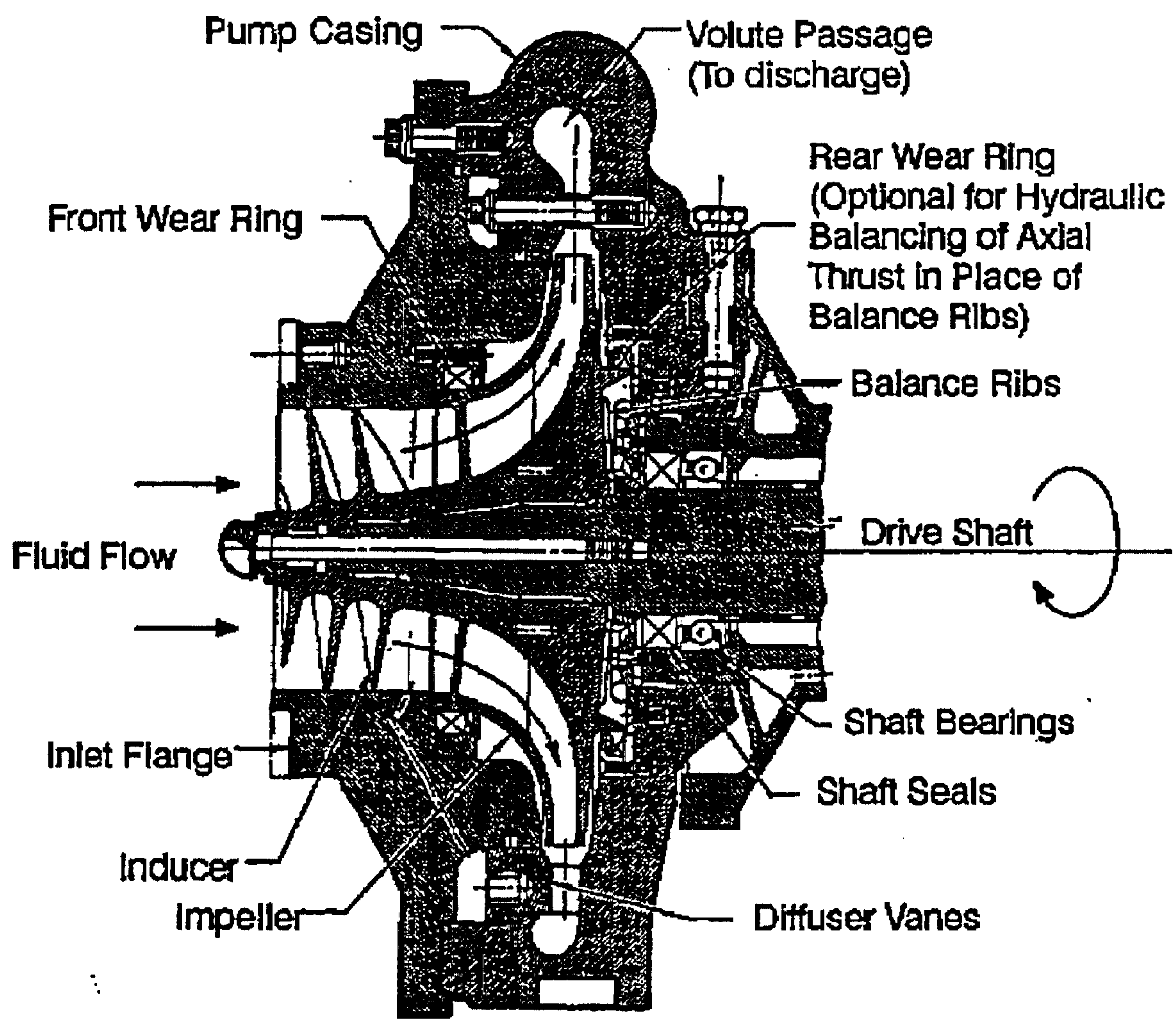
TURBOPUMP AXIAL THRUST BALANCE

- Axial thrust balance is a critical element of turbomachinery design
  - Thrust balance system is normally tailored to balance loads at the design and over the steady state operating range
  - Transient axial thrust loads are reacted by bearings or rub stops
    - Difficult to meet long life requirements using rub stops

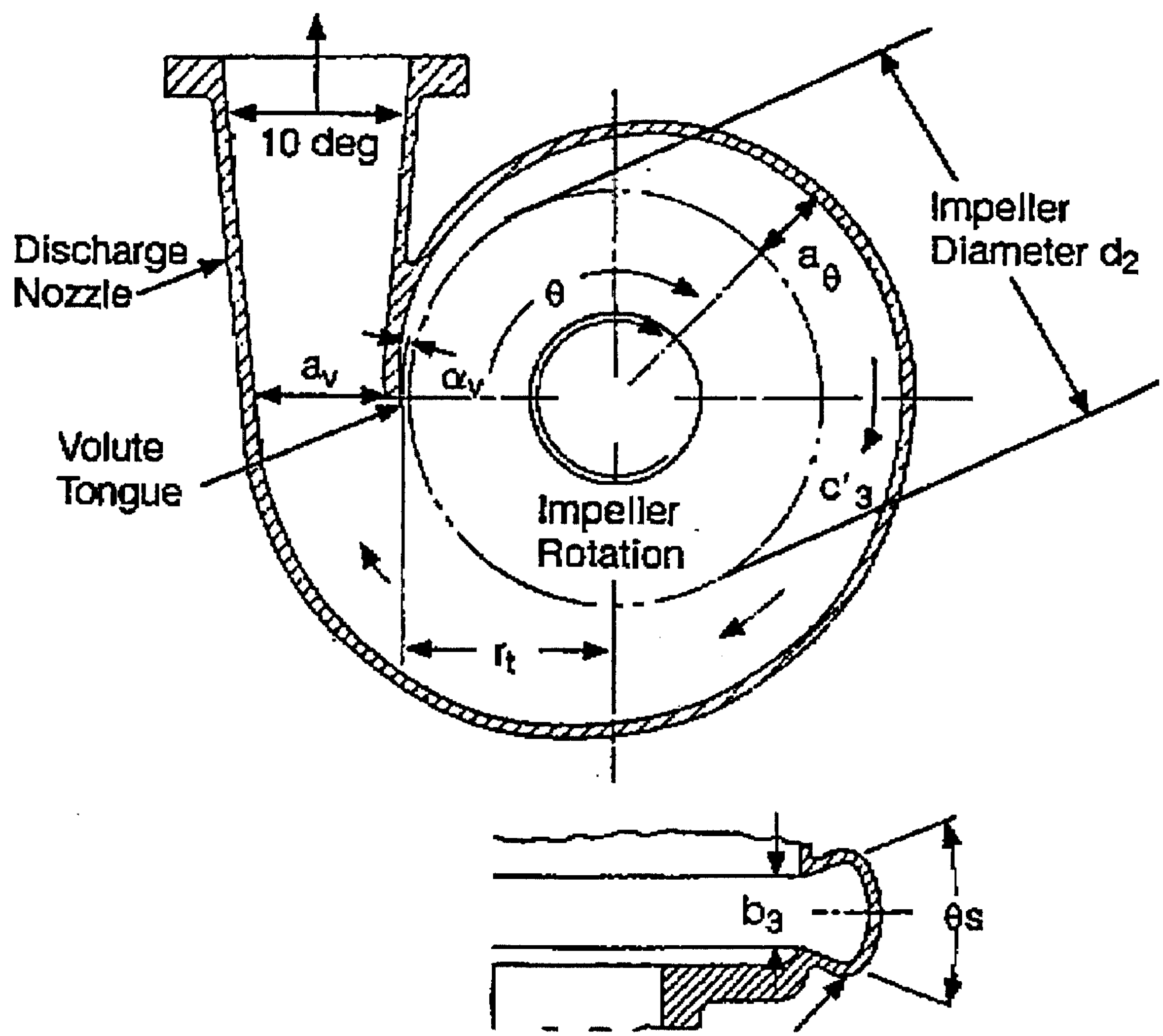
TURBOPUMP CASINGS

- Must provide the structural integrity to
  - Contain internal pressures
  - Transmit loads to mounting structure
- Provide hydrodynamically and aerodynamically efficient flow passages
  - Pump and turbine casing do not generate head or extract usable energy
  - Can contribute substantially to the loss of head or loss of energy available to turbines

TURBOPUMP CASINGS



TURBOPUMP CASINGS



TURBOPUMP CASINGS

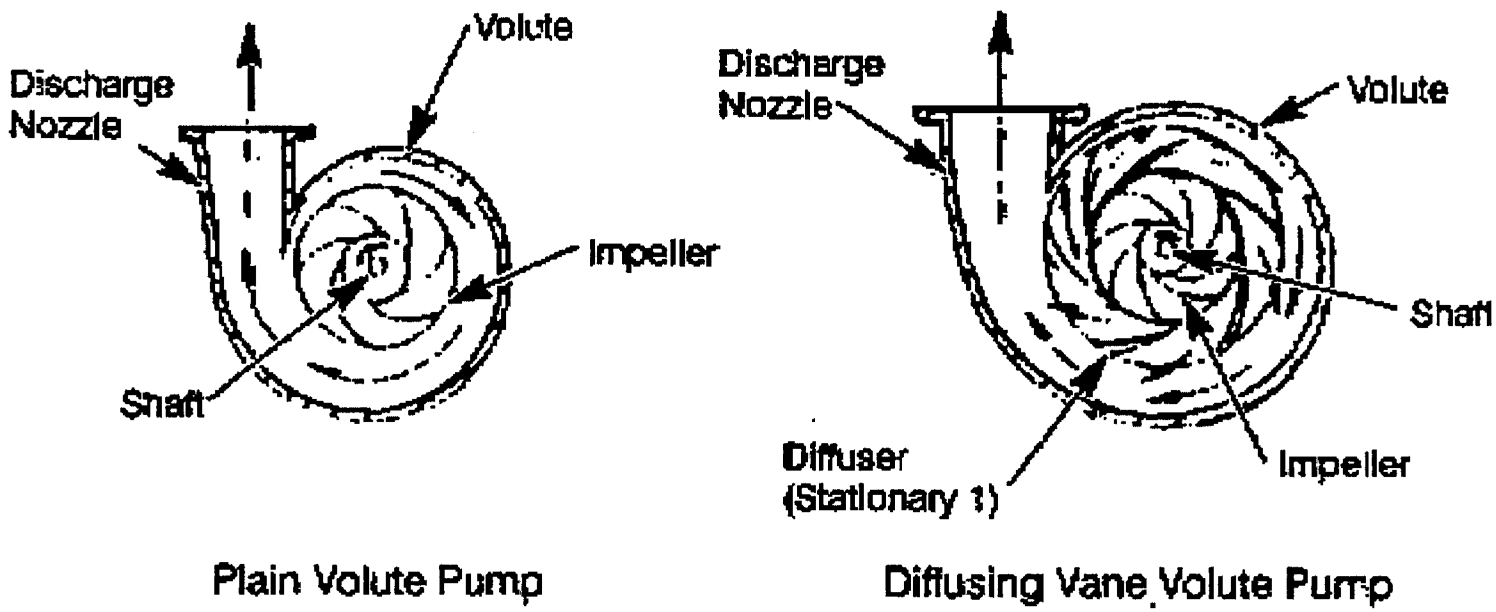


Fig. 6-39 Plain-volute and vaned-diffuser-volute centrifugal pump casings.

TURBOPUMP CASINGS

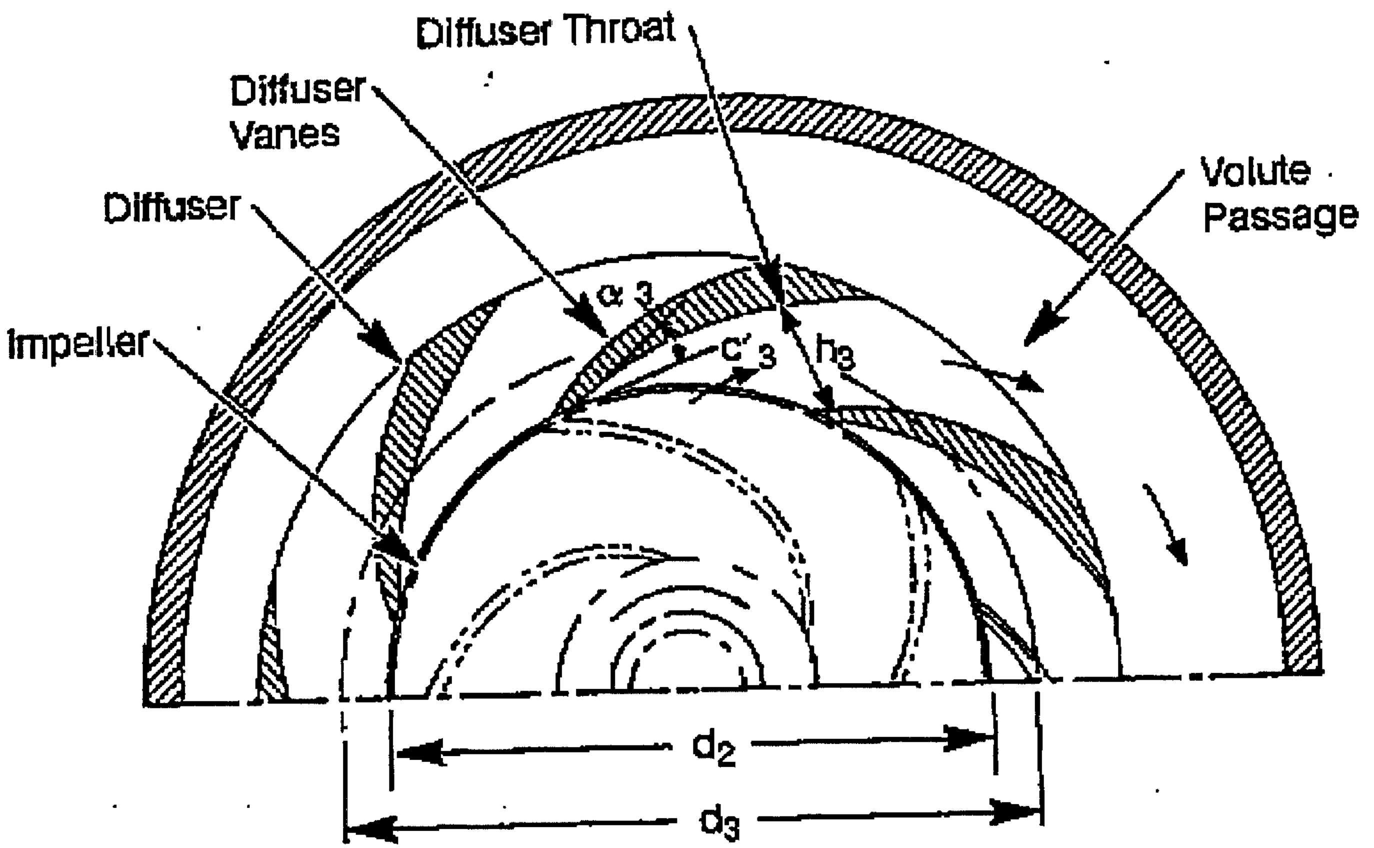


Fig. 6-43 Typical layout of the diffuser for a pump.

TURBOPUMP CASINGS

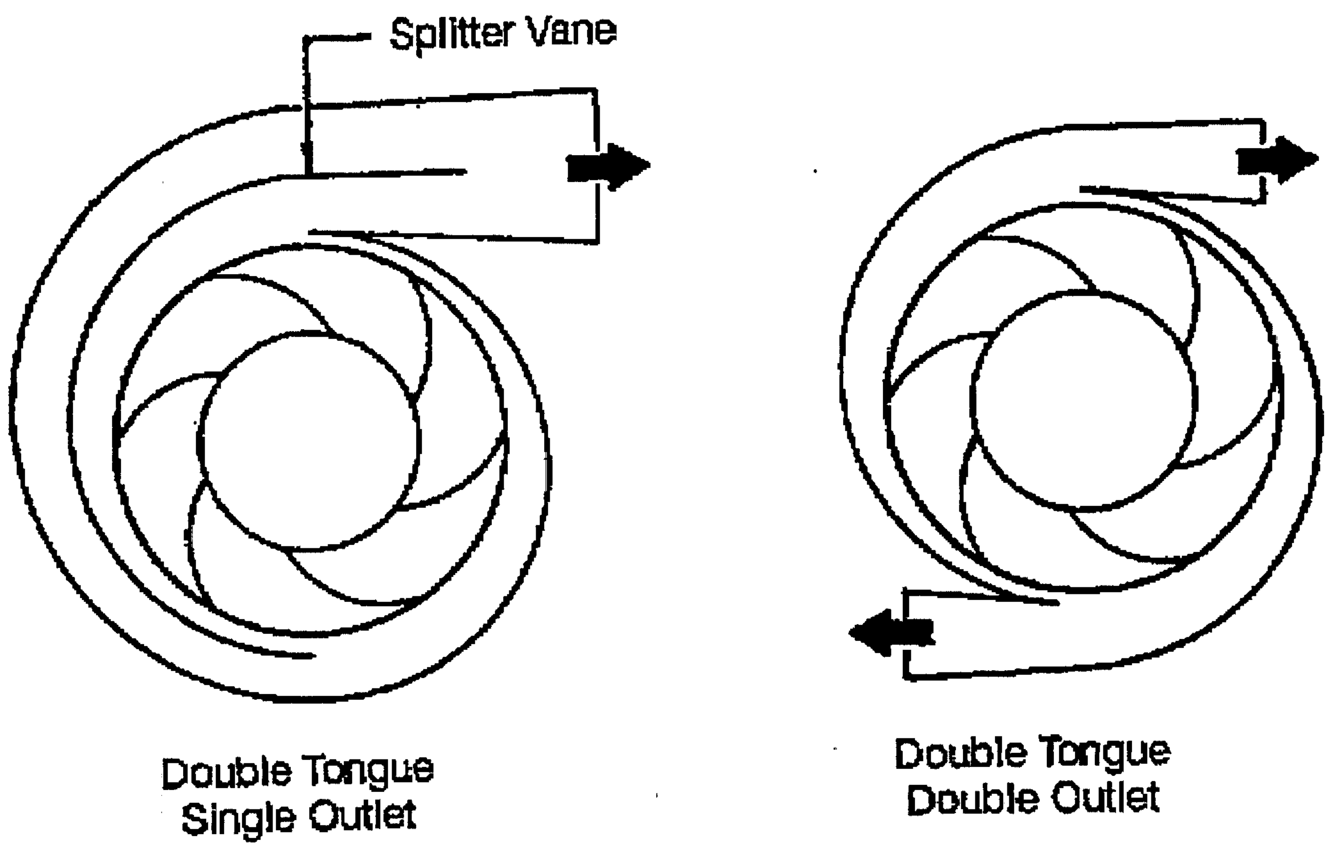
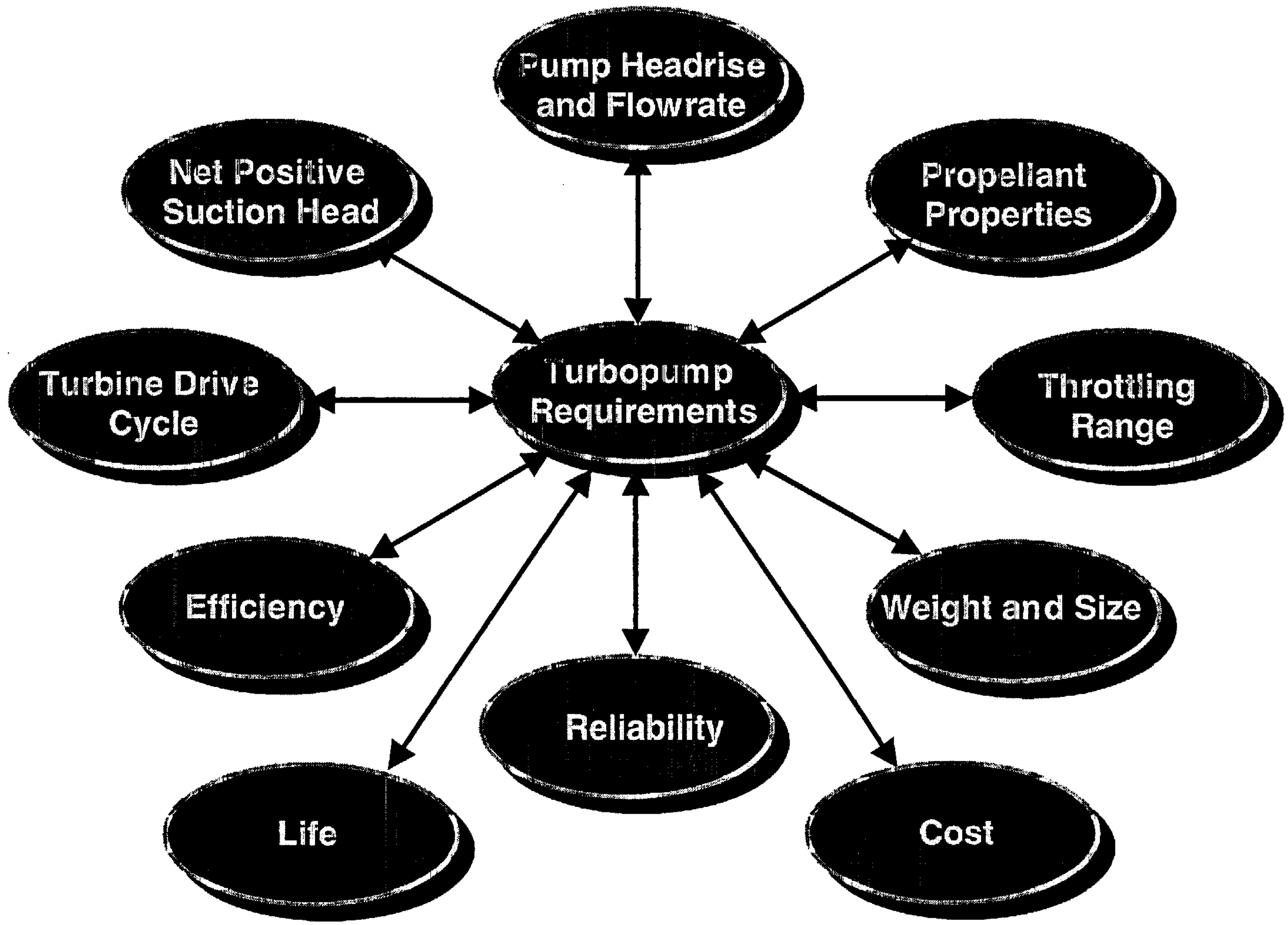


Fig. 6-42 Typical double-tongue and double-discharge volute configurations.

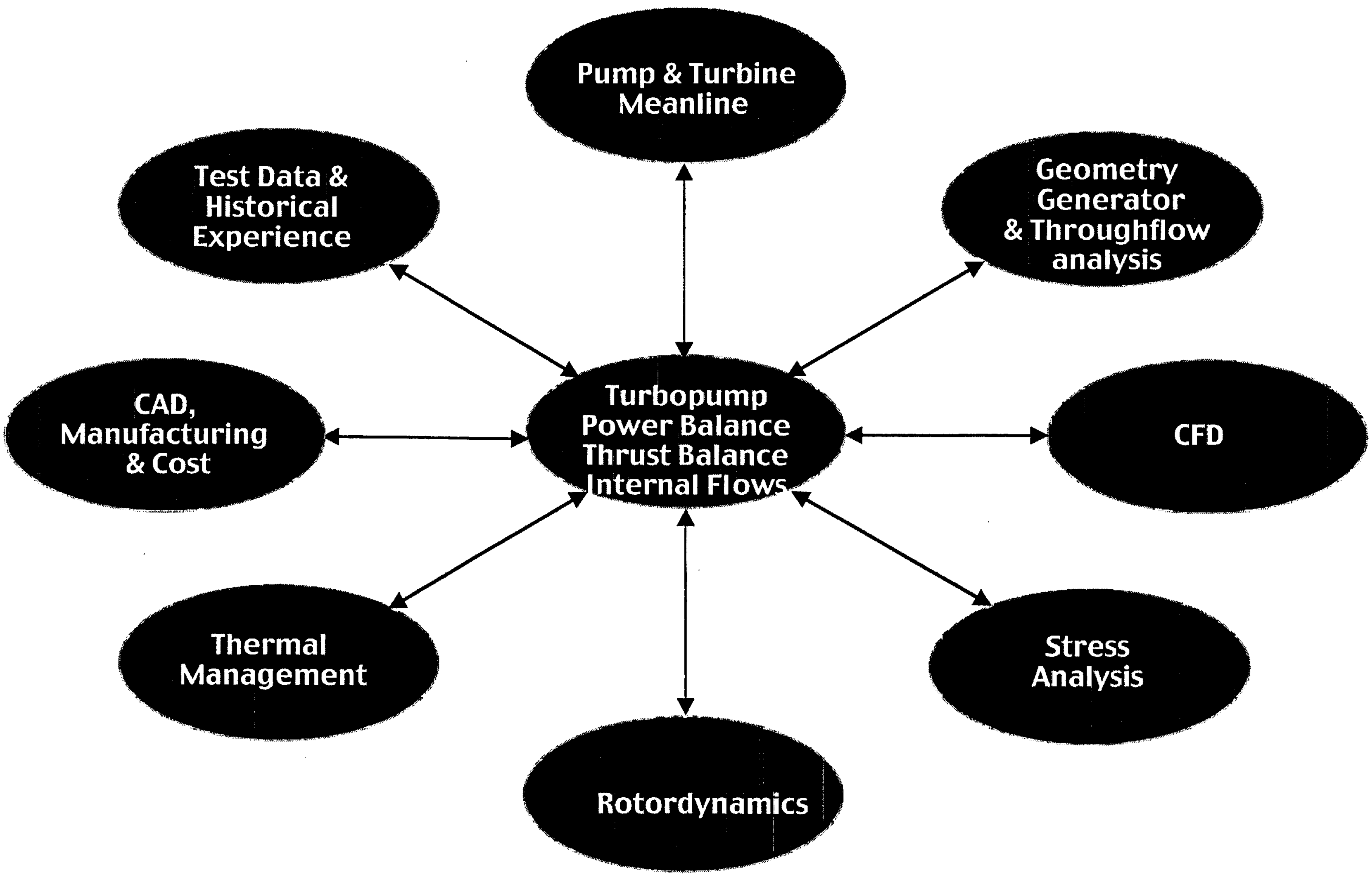
TURBOMACHINERY DESIGN PROCESS

- Like all designs rocket engine turbomachines are a compromise of many competing factors
  - Requirements are set by system needs
  - Priorities are often set by program needs and priorities
    - Typical examples
      - Design Life
      - Cost
- Turbomachinery design iterative and requires the interaction on many disciplines.

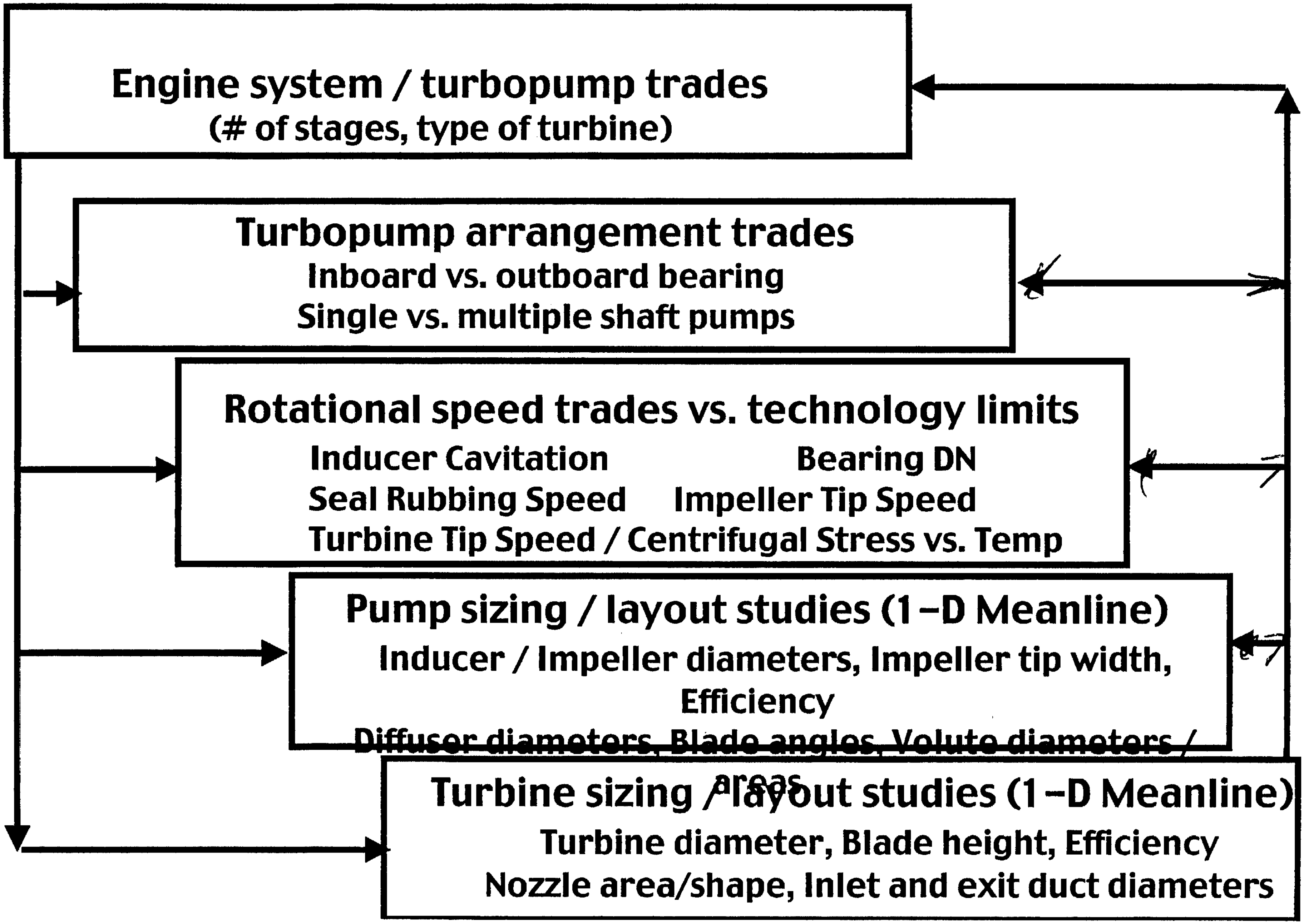
Turbopump Requirements



Preliminary Design Environment



Preliminary Design



TURBOMACHINERY DESIGN PROCESS

- Design process generally progresses through several phases
  - Conceptual
    - A machine concept that may meet requirements is established
  - Preliminary
    - Represents refinement of concept. May deviate substantially from conceptual design
  - Detailed design
    - Refined analyses and mechanical design

TURBOMACHINERY DESIGN PROCESS

- As the design matures the verification/validation process initiates
  - Testing of components
    - H_2O testing of hydrodynamic element
    - Air testing of turbine elements
    - Rig testing of bearings
  - Testing of the turbopump
  - Testing on the engine

SUMMARY
ROCKET ENGINE TURBOPUMPS

- Rocket engine turbopumps are highly complex machines
- Rocket engine turbopumps have several unique features
  - Generally very high pow~~d~~er density machines
  - Experience high fluid dynamic loads
  - Exposed to severe thermal shocks
    - Rapid starts and stops
    - Extremely high heat transfer coefficients
  - Stringent suction performance requirements to minimize tank weight

SUMMARY
ROCKET ENGINE TURBOPUMPS

- Rocket engine turbopumps have several unique features (continued)
  - Working fluids significantly impact the design
    - Oxidizers generally explosive
    - Afford almost no lubrication for bearings and seals
    - Some fuels can degrade material properties
    - Cryogenics result in severe thermal gradients
  - Life requirements are short relative to other turbomachines
    - Hundreds of cycles and a few hours of

SUMMARY
ROCKET ENGINE TURBOPUMPS

- Rocket engine turbopumps have several unique features (continued)
  - Working fluids significantly impact the design
    - Oxidizers generally explosive
    - Afford almost no lubrication for bearings and seals
    - Some fuels can degrade material properties
    - Cryogenics result in severe thermal gradients
  - Life requirements are short relative to other turbomachines
    - Hundreds of cycles and a few hours of operation for reusable systems
      - Meeting these is a challenge

SUMMARY
ROCKET ENGINE TURBOPUMPS

- Design of rocket engine turbomachines is a systems engineering challenge
  - Multiple engineering disciplines must be integrated
    - Stress
    - Structural dynamics
    - Hydrodynamics
    - Aerodynamics
    - Thermal
    - Materials and Processes

Fluid Dynamics

SUMMARY
ROCKET ENGINE TURBOPUMPS

- Design of rocket engine turbomachines is a systems engineering challenge
  - Multiple engineering disciplines must be integrated (continued)
    - Test
    - Mechanical Design
    - Rotordynamics